

IEEE Standard for Low-Rate Wireless Networks

IEEE Computer Society

Developed by the
LAN/MAN Standards Committee

STANDARDS

IEEE Std 802.15.4™-2024
(Revision of IEEE Std 802.15.4-2020)

IEEE Standard for Low-Rate Wireless Networks

Developed by the
LAN/MAN Standards Committee
of the
IEEE Computer Society

Approved 26 September 2024
IEEE SA Standards Board

Abstract: The physical layer (PHY) and medium access control (MAC) sublayer specifications for low-data-rate wireless connectivity with fixed, portable, and moving devices with no battery or very limited battery consumption requirements are defined in this standard. In addition, the standard provides modes that allow for precision ranging. PHYs are defined for devices operating in a variety of geographic regions.

Keywords: ad hoc network, IEEE 802.15.4™, low data rate, low power, LR-WPAN, mobility, PAN, personal area network, radio frequency, RF, short range, wireless, wireless network, wireless personal area network, WPAN

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2024 by the Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 12 December 2024. Printed in the United States of America.

IEEE and 802 are registered trademarks in the U.S. Patent & Trademark Office, owned by the Institute of Electrical and Electronics Engineers, Incorporated.

PDF: ISBN 979-8-8557-1315-2 STD27377
Print: ISBN 979-8-8557-1316-9 STDPD27377

IEEE prohibits discrimination, harassment, and bullying.
For more information, visit <http://www.ieee.org/web/aboutus/whatis/policies/p9-26.html>.

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

Important Notices and Disclaimers Concerning IEEE Standards Documents

IEEE Standards documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page (<https://standards.ieee.org/ipr/disclaimers.html>), appear in all IEEE standards and may be found under the heading “Important Notices and Disclaimers Concerning IEEE Standards Documents.”

Notice and Disclaimer of Liability Concerning the Use of IEEE Standards Documents

IEEE Standards documents are developed within IEEE Societies and subcommittees of IEEE Standards Association (IEEE SA) Board of Governors. IEEE develops its standards through an accredited consensus development process, which brings together volunteers representing varied viewpoints and interests to achieve the final product. IEEE standards are documents developed by volunteers with scientific, academic, and industry-based expertise in technical working groups. Volunteers involved in technical working groups are not necessarily members of IEEE or IEEE SA and participate without compensation from IEEE. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information or the soundness of any judgments contained in its standards.

IEEE makes no warranties or representations concerning its standards, and expressly disclaims all warranties, express or implied, concerning all standards, including but not limited to the warranties of merchantability, fitness for a particular purpose and non-infringement. IEEE Standards documents do not guarantee safety, security, health, or environmental protection, or compliance with law, or guarantee against interference with or from other devices or networks. In addition, IEEE does not warrant or represent that the use of the material contained in its standards is free from patent infringement. IEEE Standards documents are supplied “AS IS” and “WITH ALL FAULTS.”

Use of an IEEE standard is wholly voluntary. The existence of an IEEE standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard.

In publishing and making its standards available, IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity, nor is IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing any IEEE Standards document should rely upon their own independent judgment in the exercise of reasonable care in any given circumstances or, as appropriate, seek the advice of a competent professional in determining the appropriateness of a given IEEE standard.

IN NO EVENT SHALL IEEE BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: THE NEED TO PROCURE SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE PUBLICATION, USE OF, OR RELIANCE UPON ANY STANDARD, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE AND REGARDLESS OF WHETHER SUCH DAMAGE WAS FORESEEABLE.

Translations

The IEEE consensus balloting process involves the review of documents in English only. In the event that an IEEE standard is translated, only the English language version published by IEEE is the approved IEEE standard.

Use by artificial intelligence systems

In no event shall material in any IEEE Standards documents be used for the purpose of creating, training, enhancing, developing, maintaining, or contributing to any artificial intelligence systems without the express, written consent of the IEEE SA in advance. “Artificial intelligence” refers to any software, application, or other system that uses artificial intelligence, machine learning, or similar technologies, to analyze, train, process, or generate content. Requests for consent can be submitted using the [Contact Us](#) form.¹

Official statements

A statement, written or oral, that is not processed in accordance with the IEEE SA Standards Board Operations Manual is not, and shall not be considered or inferred to be, the official position of IEEE or any of its committees and shall not be considered to be or be relied upon as, a formal position of IEEE or IEEE SA. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that the presenter’s views should be considered the personal views of that individual rather than the formal position of IEEE, IEEE SA, the Standards Committee, or the Working Group. Statements made by volunteers may not represent the formal position of their employer(s) or affiliation(s). News releases about IEEE standards issued by entities other than IEEE SA should be considered the view of the entity issuing the release rather than the formal position of IEEE or IEEE SA.

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE or IEEE SA. However, **IEEE does not provide interpretations, consulting information, or advice pertaining to IEEE Standards documents.**

Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Since IEEE standards represent a consensus of concerned interests, it is important that any responses to comments and questions also receive the concurrence of a balance of interests. For this reason, IEEE and the members of its Societies and subcommittees of the IEEE SA Board of Governors are not able to provide an instant response to comments or questions except in those cases where the matter has previously been addressed. For the same reason, IEEE does not respond to interpretation requests. Any person who would like to participate in evaluating comments or revisions to an IEEE standard is welcome to join the relevant IEEE SA working group. You can indicate interest in a working group using the Interests tab in the Manage Profile & Interests area of the [IEEE SA myProject system](#).² An IEEE Account is needed to access the application.

Comments on standards should be submitted using the [Contact Us](#) form.¹

Laws and regulations

Users of IEEE Standards documents should consult all applicable laws and regulations. Compliance with the provisions of any IEEE Standards document does not constitute compliance to any applicable regulatory

¹ Available at: <https://standards.ieee.org/about/contact/>.

² Available at: <https://development.standards.ieee.org/myproject-web/public/view.html#landing>.

requirements. Implementers of the standard are responsible for observing or referring to the applicable regulatory requirements. IEEE does not, by the publication of its standards, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

Data privacy

Users of IEEE Standards documents should evaluate the standards for considerations of data privacy and data ownership in the context of assessing and using the standards in compliance with applicable laws and regulations.

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under U.S. and international copyright laws. They are made available by IEEE and are adopted for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making these documents available for use and adoption by public authorities and private users, neither IEEE nor its licensors waive any rights in copyright to the documents.

Photocopies

Subject to payment of the appropriate licensing fees, IEEE will grant users a limited, non-exclusive license to photocopy portions of any individual standard for company or organizational internal use or individual, non-commercial use only. To arrange for payment of licensing fees, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400; <https://www.copyright.com/>. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Updating of IEEE Standards documents

Users of IEEE Standards documents should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of amendments, corrigenda, or errata. An official IEEE document at any point in time consists of the current edition of the document together with any amendments, corrigenda, or errata then in effect.

Every IEEE standard is subjected to review at least every 10 years. When a document is more than 10 years old and has not undergone a revision process, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE standard.

In order to determine whether a given document is the current edition and whether it has been amended through the issuance of amendments, corrigenda, or errata, visit [IEEE Xplore](#) or [contact IEEE](#).³ For more information about the IEEE SA or IEEE's standards development process, visit the IEEE SA Website.

Errata

Errata, if any, for all IEEE standards can be accessed on the [IEEE SA Website](#).⁴ Search for standard number and year of approval to access the web page of the published standard. Errata links are located under the

³ Available at: <https://ieeexplore.ieee.org/browse/standards/collection/ieee>.

⁴ Available at: <https://standards.ieee.org/standard/index.html>.

Additional Resources Details section. Errata are also available in [IEEE Xplore](#). Users are encouraged to periodically check for errata.

Patents

IEEE standards are developed in compliance with the [IEEE SA Patent Policy](#).⁵

Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. If a patent holder or patent applicant has filed a statement of assurance via an Accepted Letter of Assurance, then the statement is listed on the IEEE SA Website at <https://standards.ieee.org/about/sasb/patcom/patents.html>. Letters of Assurance may indicate whether the Submitter is willing or unwilling to grant licenses under patent rights without compensation or under reasonable rates, with reasonable terms and conditions that are demonstrably free of any unfair discrimination to applicants desiring to obtain such licenses.

Essential Patent Claims may exist for which a Letter of Assurance has not been received. The IEEE is not responsible for identifying Essential Patent Claims for which a license may be required, for conducting inquiries into the legal validity or scope of Patents Claims, or determining whether any licensing terms or conditions provided in connection with submission of a Letter of Assurance, if any, or in any licensing agreements are reasonable or non-discriminatory. Users of this standard are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. Further information may be obtained from the IEEE Standards Association.

IMPORTANT NOTICE

Technologies, application of technologies, and recommended procedures in various industries evolve over time. The IEEE standards development process allows participants to review developments in industries, technologies, and practices, and to determine what, if any, updates should be made to the IEEE standard. During this evolution, the technologies and recommendations in IEEE standards may be implemented in ways not foreseen during the standard's development. IEEE standards development activities consider research and information presented to the standards development group in developing any safety recommendations. Other information about safety practices, changes in technology or technology implementation, or impact by peripheral systems also may be pertinent to safety considerations during implementation of the standard. Implementers and users of IEEE Standards documents are responsible for determining and complying with all appropriate safety, security, environmental, health, data privacy, and interference protection practices and all applicable laws and regulations.

⁵ Available at: <https://standards.ieee.org/about/sasb/patcom/materials.html>.

Participants

At the time this standard was sent to ballot, the IEEE 802.15 Working Group had the following voting members:

Clint Powell, Chair
Phil Beecher, Co-Vice Chair
Ann Krieger, Co-Vice Chair
James P. K. Gilb, Working Group Technical Editor
Thomas Almholt, Secretary

Gary Stuebing, IEEE 802.15.4me Task Group Chair
Phil Beecher, IEEE 802.15.4me Task Group Vice Chair
Tero Kivinen, IEEE 802.15.4me Technical Editor

Koorosh Akhavan
Carlos Aldana
Ghiath Al-kadi
Yasuharu Amezawa
Jean-Marie Andre
Claudio Anliker
Daisuke Anzai
Kwok Shum Au
Ankur Bansal
David Barras
Tuncer Baykas
Friedbert Berens
Ido Bettessh
Harry Bims
Lennert Bober
Monique Brown
Chris Calvert
Clint Chaplin
Run Chen
Hangyu Cho
Jinsoo Choi
Sangsun Choi
Pablo Corbalan Pelegrin
Boris Danev
Hendricus De Ruijter
Igor Dotlic
Ersen Ekrem
Ming Gan
Tim Godfrey
Robert Golshan
Kristian Granhaug
Bernhard Grosswindhager
Josef Gruber
Raphael Guimond
Jianlin Guo
Ziyang Guo
Taeyoung Ha
Hirosi Harada
James Hartman
Jerome Henry
Marco Hernandez
Chris Hett
Masayuki Hirata
Iwao Hosako

Lei Huang
Tetsushi Ikegami
Yeong Min Jang
Jinjing Jiang
Seong-Soon Joo
Josep Miquel Jornet
Volker Jungnickel
Juha Juntunen
Aniruddh Kabbinal
Vishal Kalkundrikar
Akifumi Kasamatsu
Rani Keren
Stuart Kerry
Minsoo Kim
Shoichi Kitazawa
Takumi Kobayashi
Ryuji Kohno
Alexander Krebs
vinod kristem
Wolfgang Kuechler
Thomas Kuerner
Hong Won Lee
Jaegook Lee
Mingyu Lee
Stefan Lemsitzer
Frank Leong
Huan-Bang Li
Sang-Kyu Lim
Wei Lin
Chenchen Liu
Yong Liu
Xiliang Luo
Yongsen Ma
Apurva Mody
Robert Mueller
Carl Murray
Frederic Nabki
Yukimasa Nagai
Vamadevan Namboodiri
Dries Neirynck
Jaroslaw Niewczas
Paul Nikolic
Pooria Pakrooh
Clark Palmer
Glenn Parsons

Srivaths Masthi Parthasarathi
Tushar Patel
Xiaohui Peng
Vitaly Petrov
Riku Pirhonen
Bin Qian
Mohammad Rahmani
Oded Redlich
Joerg Robert
Benjamin Rolfe
Hiroki Saito
Stephan Sand
Shigenobu Sasaki
Kamran Sayrafian
Jonathan Segev
Norihiko Sekine
Kunal P. Shah
Menashe Shahar
Stephen Shellhammer
Shimi Shilo
Youngwan So
Don Sturek
Li Sun
Li-Hsiang Sun
Takafumi Suzuki
Bin Tian
Lochan Verma
Billy Verso
Matthias Wendt
Dag Wisland
Kanke Wu
Kuan Wu
Libra Xiao
Shang-Te Yang
Xun Yang
Zhenzhen Ye
Su Khiong Yong
Kangjin Yoon
Larry Zakaib
Sven Zeisberg
Qiyue Zou

Major contributions in the revision process were received from the following individuals:

Harry Bims	Tero Kivinen	Kunal P. Shah
Hendricus De Ruijter	Clint Powell	Gary Stuebing
Chris Hett	R. K. Rannow	Don Sturek
Roger Hislop	George Robert	Billy Verso
Klaus Hueske	Benjamin Rolfe	Lisa Ward
Shoichi Kitazawa	Ruben E. Salazar Cardozo	Hidetoshi Yokota

The following members of the individual balloting committee voted on this standard. Balloters may have voted for approval, disapproval, or abstention.

Carlos Aldana	Raj Jain	Gaurav Patwardhan
Thomas Almholt	SangKwon Jeong	Arumugam Paventhian
Boon Chong Ang	Pranav Jha	Vitaly Petrov
Carol Ansley	Zhengbo Jiang	Riku Pirhonen
Butch Anton	Volker Jungnickel	Adrian Popescu
Philippe Astier	Sriniwas Kandala	Cam Posani
Kwok Shum Au	Ruslan Karmanov	Clint Powell
Phil Beecher	Piotr Karocki	R. K. Rannow
Harry Bims	Stuart Kerry	Maximilian Riegel
Maciej Borowka	Yongbum Kim	Joerg Robert
Vern Brethour	Youhan Kim	Benjamin Rolfe
William Byrd	Patrick Kinney	Ruben E. Salazar Cardozo
Radhakrishna Canchi	Shoichi Kitazawa	Stephan Sand
Paul Cardinal	Tero Kivinen	Naotaka Sato
Juan Carreon	Mallory Knodel	Reinhard Schrage
Pin Chang	Alexander Krebs	Jhony Sembiring
Steven Crowley	Takashi Kuramochi	Diana Shi
Hendricus De Ruijter	Hyeong Ho Lee	Dorothy Stanley
Lubna Dhirani	James Lepp	Eugene Stoudenmire
Xiandong Dong	Joseph Levy	Walter Struppler
Marc Emmelmann	Qinghua Li	Gary Stuebing
Matthew Fischer	Weili Liu	Don Sturek
Michael Fischer	Haiying Lu	Mark Sturza
Avraham Freedman	Yongsen Ma	Bo Sun
Matthias Fritzsche	William Rogelio Marchand Nino	Li-Hsiang Sun
Shubhanker Garg	Ignacio Marin Garcia	Bin Tian
Robert Golshan	Edward McCall	John Vergis
David Goodall	Stephen McCann	Billy Verso
Kristian Granhaug	Michael Montemurro	Xiaohui Wang
Niclas Granqvist	Ronald Murias	Yi-Hsiu Wang
Muhammad Kumail Haider	Rajesh Murthy	Lisa Ward
Mark Hamilton	Bruce Muschitz	Matthias Wendt
James Hartman	Karim Nassiri Toussi	Menzo Wentink
Jerome Henry	Dries Neirynck	Scott Willy
Marco Hernandez	Mfanasibili Nkonyane	Andreas Wolf
Werner Hoelzl	John Notor	Yu Yuan
Oliver Holland	Satoshi Oyama	Oren Yuen
Klaus Hueske	Pooria Pakrooh	Sven Zeisberg
Tetsushi Ikegami	Bansi Patel	

When the IEEE SA Standards Board approved this standard on 26 September 2024, it had the following membership:

David J. Law, *Chair*

Jon W. Rosdahl, *Vice Chair*

Gary Hoffman, *Past Chair*

Alpesh Shah, *Secretary*

Sara R. Biyabani

Ted Burse

Stephen Dukes

Doug Edwards

J. Travis Griffith

Guido R. Hertz

Ronald W. Hotchkiss

Hao Hu

Yousef Kimiagar

Joseph L. Koepfinger*

Howard Li

Xiaohui Liu

John Haiying Lu

Kevin W. Lu

Hiroshi Mano

Paul Nikolich

Robby Robson

Lei Wang

F. Keith Waters

Sha Wei

Philip B. Winston

Don Wright

*Member Emeritus

Historical participants

Many individuals have participated in the IEEE 802.15 Working Group during various stages of the standard's development. Since the initial publication, many amendments have added functionality or updated material in this standard, and now five revisions have been published. Here is a historical list of the working group participants who dedicated their valuable time, energy, and knowledge to the advancement of this standard at the time of its original publication and for its previous revisions. Many of these members also worked on amendments.

The following members of the IEEE 802.15 Working Group participated in the development of the original standard, IEEE Std 802.15.4-2003:

Robert F. Heile, *Chair*

James D. Allen, *Vice Chair*

Patrick W. Kinney, *Secretary*

Michael D. McInnis, *Assistant Secretary and Editor*

Ian C. Gifford, *Task Group 1 Chair*

Stephen J. Shellhammer, *Task Group 2 Chair*

John R. Barr, *Task Group 3 Chair*

Patrick W. Kinney, *Task Group 4 Chair*

Phil Jamieson, *Task Group 4 Vice Chair*

José A. Gutierrez, *Task Group 4 Editor-in-Chief*

Marco Naeve, *Task Group 4 Secretary*

Monique Bourgeois, *MAC Technical Editor*

Said Moridi, *PHY Technical Editor*

Phil Jamieson, *Layer Management Technical Editor*

Greg Breen, *Low-Band PHY Technical Editing*

Ed Callaway, *Networking Technical Editing*

Paul Gorday, *High-Band PHY Technical Editing*

Marco Naeve, *General Description Technical Editing*

David Cypher, *PICs/SDLs Technical Editing*

Robert D. Poor, *Coexistence Technical Editing*

Farron Dacus, *Regulatory Technical Editing*

Roberto Aiello

Masaaki Akahane

Richard Alfvin

Arun Arunachalam

Naiel Askar

Venkat I. Bahl

Daniel Bailey

Jay Bain

James Baker

Jaiganesh Balakrishnan

Anuj Batra

Timothy Blaney

Kenneth Bochike

Stan Bottoms

Mark V. Bowles

Chuck Brabenac

Soo-Young Chang

Francois Po_Shin Chin

Aik Chindapol

Craig Conkling

Anand Dabak

Kai Dombrowski

Mary DuVal

Michael Dydyk

Jason L. Ellis

Mark W. Fidler

Jeff R. Foerster

David S. Furuno

Pierre Gandolfo

Atul Garg

James Gilb

Nada Golmie

Yasuo Harada

Allen Heberling

Barry Herold

Robert Y. Huang

Eran Igler

Katsumi Ishii

Jeyhan Karaoguz

Masami Katagiri

Joy H. Kelly

Stuart J. Kerr

Yongsuk Kim

Young Hwan Kim

Günter Kleindl

Bruce P. Kraemer

DoHoon Kwon

Jim Lansford

David Leeper

Liang Li

Yeong-Chang Maa

Steven March

Ralph Mason

Jim Meyer

Leonard E. Miller

Akira Miura

Andreas Molisch

Antonio Mondragon	Chandos Rypinski	Teik-Kheong Tan
Tony Morelli	John H. Santhoff	Larry Taylor
Chiu Ngo	Mark Schrader	Stephen E. Taylor
Kei Obara	Tom Schuster	Hans vanLeeuwen
Knut Odman	Erik Schylander	Ritesh Vishwakarma
John B. Pardee	Michael Seals	Thierry Walrant
Jongun Park	Nick Shepherd	Jing Wang
Dave Patton	Gadi Shor	Fijio Watanabe
Marcus Pendergrass	William Shvodian	Mathew Welborn
Gregg Rasor	Thomas Siep	Richard Wilson
Ivan Reede	Kazimierz Siwiak	Stephen Wood
Jim Richards	Carl Stevenson	Edward G. Woodrow
Glyn Roberts	Rene Struik	Hirohisa Yamaguchi
Richard Roberts	Shigeru Sugaya	Amos Young
William Roberts	Kazuhsia Takamura	Song-Lin Young
Chris Rogers	Katsumi Takaoka	Nakache Yves-paul
Philippe Rouzet		Jim Zyren

Major contributions were received from the following individuals:

Tony Adamson	Ed Hogervorst	Niels Schutten
David Archer	Stephen Korfhage	Nick Shepherd
David Avery	Charles Luebke	Ari Singer
Venkat Bahl	Masahiro Maeda	Ralph D'Souza
Daniel Bailey	Ian Marsden	Carl Stevenson
Edul Batliwala	Chris Marshall	Mark Tilinghast
Pratik Bose	Paul Marshall	Hans Van Leeuwen
Boaz Carmeli	Fred Martin	Jacco van Muiswinkel
Farron Dacus	Ralph Mason	Luis Pereira
Martin Digon	Rod Miller	Richard Wilson
Ian C. Gifford	Phil Rudland	Wim Zwart

The following members of the IEEE 802.15 Working Group participated in the development of the first revision, IEEE Std 802.15.4-2006:

Robert F. Heile, Chair
James D. Allen, Vice Chair
Patrick W. Kinney, Assistant Vice Chair
James P. K. Gilb, Editor-in-Chief
Patrick W. Kinney, Secretary
Michael D. McInnis, Assistant Secretary and Editor
John R. Barr, Task Group 3b Chair
Reed Fisher, Task Group 3c Chair
Patrick W. Kinney, Task Group 4a Chair
Myung Lee, Task Group 5 Chair
Robert D. Poor, Task Group 4b Chair
Marco Naeve, Task Group 4b Vice Chair
Monique B. Brown, Task Group 4b Editor-in-Chief
Eric T. Gnoske, Task Group 4b Secretary
Philip E. Beecher, MAC Contributing Editor
Monique B. Brown, MAC Technical Editor
Edgar H. Callaway, Jr., MAC Contributing Editor
Francois Chin, PHY Contributing Editor
Robert C. Cragie, MAC/Security Contributing Editor
Paul Gorday, PHY Contributing Editor

James P. K. Gilb, *Draft D3 Editor-in-Chief*
Øyvind Janbu, *MAC/PHY/Security Contributing Editor*
Marco Naeve, *General Description/PICS Editor, MAC Contributing Editor*
Clinton C. Powell, *PHY Technical Editor*
Joseph Reddy, *Security Contributing Editor*
Zachary Smith, *MAC Contributing Editor*
René Struik, *Security Contributing Editor*
Andreas C. Wolf, *PHY Contributing Editor*

Roberto Aiello	Tian-Wei Huang	Philip Orlik
Richard Alfvin	Hideto Ikeda	Laurent Ouvry
Mikio Aoki	Tetsushi Ikegami	John Pardee
Takashi Arita	Adrian Jennings	Nirmalendu Patra
Larry Arnett	Ho-In Jeon	Dave Patton
Arthur Astrin	Tzyy Hong Jiang	Xiaoming Peng
Yasaman Bahreini	David Julian	Tony Pollock
Jay Bain	Jeyhan Karaoguz	Vidyasagar Premkumar
Alan Berkema	Michael Kelly	Yihong Qi
Bruce Bosco	Stuart Kerry	Raad Raad
Mark Bowles	Jae-Hyon Kim	Pekka Ranta
Charles Brabenac	Jaeyoung Kim	Dani Raphaeli
David Brenner	Jinkyeong Kim	Gregg Rasor
Vern Brethour	Yongsuk Kim	Charles Razzell
Ronald Brown	Kursat Kimyacioglu	Ivan Reede
Bill Carney	Matthias Kindler	Yuko Rikuta
Kuo-Hsin Chang	Guenther Kleindl	Terry Robar
Jonathon Cheah	Ryuji Kohno	Glyn Roberts
Kwan-Wu Chin	Mike Krell	Richard Roberts
Sarm-Goo Cho	Yasushi Kudo	Benjamin A. Rolfe
Sungsoo Choi	Akiomi Kunisa	Philippe Rouzet
Yun Choi	Yuzo Kuramochi	Chandos Rypinski
Chun-Ting Chou	Jiun-You Lai	Ali Sadri
Manoj Choudhary	Ismail Lakkis	Saeid Safavi
Celestino Corral	John Lampe	Zafer Sahinoglu
Joe Decuir	Kyung Kuk Lee	Tomoki Saito
Javier Del Prado Pavon	Wooyong Lee	Syed Saleem
Kai Dombrowski	David Leeper	Kamran Sayrafian
Stefan Drude	Huan-Bang Li	Jean Schwoerer
Amal Ekbal	Haixiang Liang	Erik Schylander
Jason Ellis	Ian Macnamara	Alireza Seyed
Shahriar Emami	Akira Maeki	Sanjeev Sharma
Paul Everest	Patricia Martigne	Siddharth Shetty
Mark W. Fidler	Abbie Mathew	John Shi
Kris Fleming	Taisuke Matsumoto	Shusaku Shimada
Amir Freund	Gustaf Max	Yuichi Shiraki
Camillo Gentile	Michael McLaughlin	Gadi Shor
Ian Gifford	Charlie Mellone	William Shvodian
Sung-Wook Goh	Klaus Meyer	Thomas Siep
Sorin Goldenberg	Samuel Mo	Michael Sim
Vivek Gupta	Andreas Molisch	Kazimierz Siwiak
Rainer Hach	Mark Moore	V. Somayazulu
Robert Hall	Ken Naganuma	Amjad Soomro
Shinsuke Hara	Yves-Paul Nakache	Carl Stevenson
Jeff Harris	Hiroyuki Nakase	Kazuaki Takahashi
Allen Heberling	Saishankar Nandagopalan	Kenichi Takizawa
Eric Heinze	Chiu Ngo	Teik-Kheong Tan
Barry Herold	Erwin Noble	Mike Tanahashi
Keisuke Higuchi	John O'Conor	Yasushi Tanaka
Jin-Meng Ho	Knut Odman	James Taylor
Patrick Houghton	Hiroyo Ogawa	Arnaud Tonnerre
Robert Huang	Yasuyuki Okuma	Ichihiko Toyoda

Jerry Upton
Bart Van Poucke
Chris Weber
Matthew Welborn
Magnus Wiklund

Gerald Wineinger
Patrick Worfolk
Tracy Wright
Hirohisa Yamaguchi
Kamya Yekeh Yazdandoost

Su-Khiong Yong
Zhan Yu
Serdar Yurdakul
Mahmoud Zadeh
Bin Zhen

Major contributions in the revision process were received from the following individuals:

Jon Adams
Helmut P. Adamski
Jonathan Avey
Jon Beniston
Bernd Grohmann
José A. Gutierrez
Jesper Holm
ZhiJian Hu
Phil A. Jamieson
Yuen-Sam Kwok

Colin Lanzl
Myung Lee
Zhongding Lei
Liang Li
Yong Liu
Frederick Martin
Frank Poegel
Matthias Scheide
D. C. Seward

Huai-Rong Shao
Mark Shea
Stephen J. Shellhammer
Mark A. Tillinghast
Johannes Van Leeuwen
Richard Wilson
Ping Xiong
Bing Xu
ChenYang Yang
Chunhui Zhu

The following members of the IEEE 802.15 Working Group participated in the development of the second revision, IEEE Std 802.15.4-2011:

Robert F. Heile, Chair
Rick Alfvin, Co-Vice Chair
Patrick W. Kinney, Co-Vice Chair
James P. K. Gilb, Working Group Technical Editor
Patrick W. Kinney, Secretary

James P. K. Gilb, Task Group 4i Chair and Technical Editor

Emad Afifi
Gahng-Seop Ahn
Roberto Aiello
Arthur Astrin
Taehan Bae
Michael Bahr
John Barr
Anuj Batra
Tuncer Baykas
Philip E. Beecher
Ashutosh Bhatia
Ghulam Bhatti
Gary Birk
Mathew Boytim
Peter David Bradley
Nancy Bravin
David Britz
Monique B. Brown
Sverre Brubk
Brian Buchanan
John Buffington
Kiran Bynam
Brent Cain
Edgar H. Callaway
Chris Calvert

Ruben E. Salazar Cardozo
Douglas Castor
Jaesang Cha
Russell Chandler
Kuor-Hsin Chang
Soo-Young Chang
Clint Chaplin
Hind Chebbo
Chang-Soon Choi
Sangsung Choi
Ciaran Connell
David Cypher
Matthew Dahl
David Davenport
Mark Dawkins
Hendricus de Ruijter
Upkar Dhaliwal
Gang Ding
Paul Dixon
Guido Dolmans
Igor Dotlic
Michael Dow
Dietmar Eggert
David Evans
Charles Farlow

John Farserotu
Jeffrey Fischbeck
Mike Fischer
George Flammer
Ryosuke Fujiwara
Noriyasu Fukatsu
Kiyoshi Fukui
John Geiger
Gregory Gillooly
Tim Godfrey
Paul Gorday
Elad Gottlib
Robert Hall
Shinsuke Hara
Hiroshi Harada
Timothy Harrington
Rodney Hemminger
Marco Hernandez
Garth Hillman
Jin-Meng Ho
Wei Hong
Srinath Hosur
David Howard
Jung-Hwan Hwang
Tacho Hwang

Ichirou Ida	Robert Moskowitz	Steve Shearer
Tetsushi Ikegami	Hamilton Moy	Stephen Shellhammer
Akio Iso	Peter Murray	Shusaku Shimada
Yeong Min Jang	Theodore Myers	Chang Sub Shin
Adrian Jennings	Chiu Ngo	Cheol Ho Shin
Wuncheol Jeong	Paul Nikolich	Michael Sim
Steven Jillings	Hirohito Nishiyama	Jonathan Simon
Noh-Gyoung Kang	David Olson	Jaeseung Son
Tae-Gyu Kang	Okundi Omeni	Paul Stadnik
Shuzo Kato	Ryoji Ono	René Struik
Tatsuya Kato	Laurent Ouvry	Chin-Sean Sum
Jeritt Kent	James Pace	Hui-Hsia Sung
Prithpal Khakuria	Hyung-II Park	Gu Sungi
Dae Ho Kim	Jahng Park	Kenichi Takizawa
Dong-Sun Kim	Seung-Hoon Park	Hirokazu Tanaka
Dukhyun Kim	Taejoon Park	Larry Taylor
Jaehwan Kim	Ranjeet Patro	Mark Thompson
Jeffrey King	Al Petrick	James Tomicik
Ryuji Kohno	Dalibor Pokrajac	Ichihiko Toyoda
Fumihide Kojima	Daniel Popa	David Tracey
Bruce Kraemer	Stephen Pope	Khanh Tran
Raymond Krasinski	Clinton C. Powell	Jerry Upton
Masahiro Kuroda	Richard Powell	Jana van Greunen
John Lampe	Chang-Woo Pyo	Hartman van Wyk
Zhou Lan	Mohammad Rahman	Michel Veillette
Khanh Le	Sridhar Rajagopal	Billy Verso
Cheolhyo Lee	Jayaram Ramasastry	Bhupender Virk
Hyungsoo Lee	Marc Reed	Joachim Walewski
Myung Lee	Ivan Reede	Junyi Wang
Daniel Lewis	Richard Roberts	Quan Wang
Huan-Bang Li	Craig Rodine	Xiang Wang
Liang Li	June Chul Roh	Andy Ward
Sang-Kyu Lim	Benjamin A. Rolfe	Scott Weikel
Jeremy Link	Seung-Moon Ryu	Nicholas West
Mike Lynch	Didier Sagan	Mark Wilbur
Robert Mason	Kentaro Sakamoto	Ludwig Winkel
Tomokuni Matsumura	Will San Filippo	Eun Tae Won
Jeff McCullough	H. Sanderford	Alan Chi Wai Wong
Michael McGillan	Kamran Sayrafian	Tao Xing
Michael D. McInnis	Timothy Schmidl	Wen-Bin Yang
Michael McLaughlin	Michael Schmidt	Yang Yang
Charles Millet	Jean Schwoerer	Kazuyuki Yasukawa
Siamak Mirnezami	Cristina Seibert	Kamya Yazdandoost
Rishi Mohindra	Neal Seidl	Kaoru Yokoo
Emmanuel Monnerie	Kunal Shah	Mu Zhao
Rajendra Moorti		Bin Zhen

Major contributions in the revision process were received from the following individuals:

Philip E. Beecher	Clint Chaplin	Clinton C. Powell
Vern Brethour	James P. K. Gilb	Benjamin A. Rolfe
Monique B. Brown	Patrick W. Kinney	Timothy Schmidl
Edgar H. Callaway	Michael D. McInnis	René Struik
Kuor-Hsin Chang		Billy Verso

The following members of the IEEE 802.15 Working Group participated in the development of the third revision, IEEE Std 802.15.4-2015:

Robert F. Heile, Chair
Rick Alvin, Co-Vice Chair
Patrick W. Kinney, Co-Vice Chair
James P. K. Gilb, Working Group Technical Editor
Patrick W. Kinney, Secretary

Patrick W. Kinney, 802.15 Maintenance Committee Chair
Benjamin A. Rolfe, 802.15 Maintenance Committee Vice Chair
James P. K. Gilb, Technical Editor

Mounir Achir	Shinsuke Hara	Robert Moskowitz
Keiji Akiyama	Timothy Harrington	Jinesh P. Nair
Arthur Astrin	James Hartman	Chiu Ngo
Philip Beecher	Marco Hernandez	Paul Nikolich
Frederik Beer	Ken Hiraga	John Notor
Chandrashekhar P. S. Bhat	Iwao Hosako	Hiroyo Ogawa
Kiran Bynam	Yeong Min Jang	Taejoon Park
Edgar Callaway	Seong-Soo Joo	Glenn Parsons
Chris Calvert	Akifumi Kasamatsu	Charles Perkins
Radhakrishna Canchi	Shuzo Kato	Albert Petrick
Kapseok Chang	Toyoyuki Kato	Clinton C. Powell
Soo-Young Chang	Jeritt Kent	Verotiana Rabariaona
Clint Chaplin	Jaehwan Kim	Ivan Reede
Stephen Chasko	Younghoo Kim	Richard Roberts
Paul Chilton	Shoichi Kitazawa	Ruben E. Salazar Cardozo
Sangsung Choi	Tero Kivinen	Noriyuki Sato
Hendricus de Ruijter	Ryuji Kohno	Norihiko Sekine
Guido Dolmans	Fumihide Kojima	Kunal Shah
Igor Dotlic	Thomas Kuerner	Stephen Shellhammer
Stefan Drude	Byung-Jae Kwak	Shusaku Shimada
Dietmar Eggert	Jae Seung Lee	Gary Stuebing
Shahriar Emami	Myung Lee	Don Sturek
Andrew Estrada	Sangjae Lee	Mineo Takai
David Evans	Huan-Bang Li	Kou Togashi
George Flammer	Liang Li	Billy Verso
Kiyoshi Fukui	Qing Li	Gabriel Villardi
Matthew Gillmore	Michael Lynch	Brian Weis
Tim Godfrey	Itaru Maekawa	Makoto Yaita
Elad Gottlib	Hiroyuki Matsumura	Peter Yee
Jussi Haapola	Michael McLaughlin	Yu Zeng
Rainer Hach	Michael McInnis	Chunhui (Allan) Zhu
	Kenichi Mori	

Major contributions in the revision process were received from the following individuals:

Philip Beecher	Jeritt Kent	Benjamin A. Rolfe
Monique Brown	Patrick W. Kinney	Ruben E. Salazar Cardozo
Edgar Callaway	Tero Kivinen	Cristina Seibert
Soo-Young Chang	Amarjeet Kumar	Kunal Shal
James P. K. Gilb	Michael McInnis	Shusaku Shimada
Tim Godfrey	Robert Moskowitz	Chin-Sean Sum
Jussi Haapola	Clinton C. Powell	Larry Taylor
Timothy Harrington	Verotiana Rabariaona	Billy Verso

The following members of the IEEE 802.15 Working Group participated in the development of the fourth revision, IEEE Std 802.15.4-2020:

Robert F. Heile, Chair
Rick Alvin, Co-Vice Chair
Patrick W. Kinney, Co-Vice Chair
James P. K. Gilb, Working Group Technical Editor
Patrick W. Kinney, Secretary

Gary Stuebing, 802.15.4nd Task Group Chair
Don Sturek, 802.15.4nd Task Group Vice Chair
Kunal P. Shah, 802.15.4nd Technical Editor

Hendrik Ahlendorf	Christopher Hett	Michael McInnis
Koorosh Akhavan	Jay Holcomb	Apurva Mody
Bernd Baer	Oliver Holland	Ayman Naguib
David Barras	Iwao Hosako	Jaroslaw Niewczas
Tuncer Baykas	Brima Ibrahim	Paul Nikolicz
Philip Beecher	Tetsushi Ikegami	Philip Orlik
Friedbert Berens	Yeong Min Jang	Aditya Padaki
Lennert Bober	Seongah Jeong	Glenn Parsons
Monique Brown	Seong-Soo Joo	Charles Perkins
Chris Calvert	Volker Jungnickel	Albert Petrick
Radhakrishna Canchi	Paul Kettle	Joe Polland
Jaesang Cha	Shoichi Kitazawa	Clinton Powell
Matthew Chang	Tero Kivinen	Demir Rakanovic
Soo-Young Chang	Daniel Knobloch	Ivan Reede
Clint Chaplin	Ryuji Kohno	Joerg Robert
Sangsung Choi	Fumihide Kojima	Benjamin Rolfe
Boris Danev	Ann Krieger	Ren Sakata
Luc Darmon	Thomas Kuerner	Ruben E. Salazar Cardozo
Hendricus De Ruijter	Jack Lee	Ioannis Sarris
Brandon Dewberry	Mingyu Lee	Peter Sauer
Anthony Fagan	Frank Leong	Nikola Serafimovski
Matthew Gillmore	Huan-Bang Li	Tushar Shah
Tim Godfrey	Zheda Li	Stephen Shellhammer
Jianlin Guo	Sang-Kyu Lim	Karthik Srinivasagopalan
Joachim Hammerschmidt	Thomas Lorbach	Billy Verso
Shinsuke Hara	Masood Maqbool	Johannes Wechsler
Hiroshi Harada	Vinayagam Mariappan	Brian Weis
Timothy Harrington	Alejandro Marquez	Peter Yee
Chris Hartman		Shaun Yu

Major contributions in the revision process were received from the following individuals:

Harry Bims	Tero Kivinen	Kunal P. Shah
Hendricus De Ruijter	Clint Powell	Gary Stuebing
Chris Hett	R. K. Rannow	Don Sturek
Roger Hislop	George Robert	Billy Verso
Klaus Hueske	Benjamin Rolfe	Lisa Ward
Shoichi Kitazawa	Ruben E. Salazar Cardozo	Hidetoshi Yokota

Introduction

This introduction is not part of IEEE Std 802.15.4-2024, IEEE Standard for Low-Rate Wireless Networks.

This is the fifth revision of IEEE Std 802.15.4. From the beginning, the goal of the IEEE 802.15 Working Group was to produce a standard that enabled very low-cost, low-power communications. The initial standard, IEEE Std 802.15.4-2003, defined two optional physical layers (PHYs), operating in different frequency bands with a simple and effective medium access control (MAC).

In 2006, the standard was revised and added two more PHY options. The MAC remained backward compatible, but the revision added MAC frames with an increased version number and a variety of MAC enhancements, including the following:

- Support for a shared time base with a data timestamping mechanism
- Support for beacon scheduling
- Synchronization of broadcast messages in personal area networks (PANs) using superframe structure
- Improved MAC layer security

In 2011, the standard was revised to include the three amendments approved subsequent to the 2006 revision. This effort added four more PHY options along with the MAC capability to support ranging. Additionally, the organization of the standard was changed so that each PHY would have a separate clause, and the MAC clause was split into functional description, interface specification, and security specification.

The 2015 revision of the standard was created to roll in the amendments approved subsequent to the 2011 revision: six PHY amendments and one MAC amendment, with corrigenda and clarifications. The features added by the amendments include the following:

- Enhanced frame formats maintaining backward compatibility
- Information Elements (IEs)
- Channel agility
- Extended superframe options
- Low-energy mechanisms
- An enhanced acknowledgment frame that can carry data and can be secured
- Prioritized channel access
- A variety of new PHY modulation, coding, and band options to support a wide variety of application needs including radio frequency identification (RFID), smart utility networks (SUNs), television white space (TVWS) operation, low-energy critical infrastructure monitoring (LECIM), and rail communications and control (RCC)

Much of the corrigenda and clarifications were collected from requests from individuals after the revision in 2011. Major corrigenda items included changes to the security text to correct errors and clarify the text, removal of the encrypt only mode, addition of security policy checks for the IEs, corrections regarding personal area network identifier (PAN ID) compression behavior to eliminate ambiguous specification, and changes to the IEs subclauses to include more information necessary for users of this standard.

The 2020 revision of the standard was created to include six approved amendments subsequent to the 2015 revision. This effort added two more PHY amendments and one MAC amendment, with corrigenda and clarifications. The features added by the amendments include the following:

- A variety of new PHY modulation, coding, and band options to support a wide variety of application needs including smart utility networks (SUNs), China medical band (CMB), ternary amplitude shift keying (TASK) and rate switch Gaussian frequency shift keying (RS-GFSK)

Much of the corrigenda and clarifications were collected from requests from individuals after the revision in 2015. Major corrigenda items included changes to the transmission order of the address field.

This current revision of the standard was created to include four amendments and one corrigendum subsequent to the 2020 revision. The features added by the amendments include the following:

- Enhanced ranging
- Improved robustness in interfered channels
- Enhanced security using cryptographic algorithm agility
- Data rate extensions for the SUN FSK modulation and channel parameters.

Contents

1.	Overview.....	40
1.1	Scope.....	40
1.2	Purpose.....	40
1.3	Word usage	40
2.	Normative references	41
3.	Definitions, acronyms, and abbreviations.....	42
3.1	Definitions	42
3.2	Acronyms and abbreviations	43
4.	Format conventions.....	48
4.1	General.....	48
4.2	Fields.....	48
4.3	Numbers.....	49
4.4	Strings	49
4.5	Transmission order	49
4.5.1	Address field	49
4.5.2	Vendor OUI/CID transmission order.....	50
4.6	Reserved fields and values.....	50
5.	General description	51
5.1	Introduction.....	51
5.2	Special application spaces	51
5.2.1	General.....	51
5.2.2	Radio frequency identification (RFID).....	51
5.2.3	Medical body area network (MBAN) services	51
5.2.4	China medical band (CMB).....	52
5.3	Components of the IEEE 802.15.4 WPAN.....	52
5.4	Network topologies.....	52
5.4.1	General.....	52
5.4.2	Star network formation	53
5.4.3	Peer-to-peer network formation.....	53
5.5	Architecture	53
5.5.1	General.....	53
5.5.2	PHY	54
5.5.3	MAC sublayer.....	55
5.6	Functional overview	55
5.6.1	Scheduled access.....	55
5.6.2	Data transfer model.....	55
5.6.3	Frame structure	56
5.6.4	Information element (IEs).....	56
5.6.5	Access methods.....	57
5.6.6	Power consumption considerations	57
5.6.7	Security	58
5.6.8	Enabling spectrum resource measurement capability.....	59
5.7	Concept of primitives.....	60

6.	MAC functional description	61
6.1	Optional features.....	61
6.2	Device types and conventions.....	61
6.3	Channel access.....	61
6.3.1	Interframe space (IFS)	61
6.3.2	Random access methods	62
6.4	Starting and maintaining PANs	63
6.4.1	Scanning through channels	63
6.4.2	Starting and realigning a PAN.....	65
6.5	Synchronization	66
6.5.1	General.....	66
6.5.2	Requesting enhanced beacons	66
6.5.3	Timestamps	67
6.6	Transmission, reception, and acknowledgment.....	68
6.6.1	Transmission.....	68
6.6.2	Reception and rejection	69
6.6.3	Use of acknowledgments and retransmissions	71
6.6.4	Transmission timing restrictions.....	72
6.6.5	Guard time	73
6.6.6	Transmission scenarios	74
7.	MAC frame formats.....	77
7.1	Device extended address.....	77
7.2	General MAC frame format.....	77
7.2.1	General.....	77
7.2.2	Frame Control field.....	78
7.2.3	Sequence Number field.....	81
7.2.4	Destination PAN ID field	82
7.2.5	Destination Address field.....	82
7.2.6	Source PAN ID field.....	82
7.2.7	Source Address field.....	82
7.2.8	Auxiliary Security Header field.....	82
7.2.9	IE field	82
7.2.10	Frame Payload field	83
7.2.11	FCS field	83
7.3	Format of individual frame types.....	85
7.3.1	Beacon frame format	85
7.3.2	Data frame format.....	89
7.3.3	Ack frame format.....	90
7.3.4	MAC Command frame format.....	91
7.3.5	Multipurpose frame format.....	92
7.3.6	Extended frame format	95
7.4	IEs	95
7.4.1	IE list termination	95
7.4.2	Header IEs.....	96
7.4.3	Payload IEs	99
7.4.4	Nested IE.....	100
7.5	MAC commands	106
7.5.1	Command ID field	106
7.5.2	Beacon Request command.....	107
7.5.3	Enhanced Beacon Request command	107
7.5.4	Coordinator Realignment command.....	108

7.5.5	Vendor Specific command.....	109
8.	MAC services	110
8.1	Overview.....	110
8.2	MAC management service.....	110
8.2.1	Primitives supported by the MLME-SAP interface.....	110
8.2.2	Common requirements for MLME primitives.....	111
8.2.3	SecurityParameterDescriptor.....	113
8.2.4	Communications notification primitives	113
8.2.5	Primitives for reading and writing PIB attributes	118
8.2.6	Primitives for resetting the MAC sublayer.....	121
8.2.7	Primitives for specifying the receiver enable time	122
8.2.8	Primitives for channel scanning.....	126
8.2.9	Primitives for updating the superframe configuration.....	130
8.2.10	Primitives for Beacon Generation.....	131
8.3	MAC data service	135
8.3.1	General.....	135
8.3.2	Ranging.....	135
8.3.3	TxOptions	141
8.3.4	MCPS-DATA.request.....	142
8.3.5	MCPS-DATA.confirm.....	145
8.3.6	MCPS-DATA.indication	147
8.3.7	MCPS-PURGE.request.....	149
8.3.8	MCPS-PURGE.confirm.....	150
8.4	MAC constants and PIB attributes.....	150
8.4.1	General.....	150
8.4.2	MAC constants	150
8.4.3	MAC PIB attributes	151
9.	Security	159
9.1	Overview.....	159
9.2	Functional description.....	159
9.2.1	General.....	159
9.2.2	Outgoing frame security procedure	159
9.2.3	KeyDescriptor lookup procedure.....	161
9.2.4	Incoming frame security procedure, Security Enabled field is set to one	162
9.2.5	Incoming frame security procedure, Security Enabled field is set to zero	164
9.2.6	DeviceDescriptor lookup procedure	165
9.2.7	SecurityLevelDescriptor lookup procedure	165
9.2.8	Incoming IE security level checking procedure	165
9.2.9	Incoming IE key usage policy checking procedure	166
9.2.10	Incoming security level checking procedure	166
9.2.11	Incoming key usage policy checking procedure.....	167
9.3	Security operations	167
9.3.1	Integer and octet representation.....	167
9.3.2	AEAD nonce.....	168
9.3.3	AEAD prerequisites	169
9.3.4	AEAD transformation data representation	169
9.3.5	AEAD inverse transformation data representation	171
9.4	Auxiliary security header.....	172
9.4.1	General.....	172
9.4.2	Security Control field.....	172

9.4.3	Frame Counter field	174
9.4.4	Key Identifier field.....	175
9.5	Security-related MAC PIB attributes.....	175
9.5.1	Generic PIB attributes.....	175
9.5.2	secAeadAlgorithm	176
9.5.3	secKeyIdLookupDescriptor	176
9.5.4	secKeyDescriptor	176
9.5.5	secKeyDeviceFrameCounterDescriptor	178
9.5.6	secKeyUsageDescriptor.....	178
9.5.7	secKeyIeUsageDescriptor.....	179
9.5.8	secDeviceDescriptor	179
9.5.9	secSecurityLevelDescriptor	179
9.5.10	secIeSecurityLevelDescriptor	180
10.	Optional features.....	181
10.1	General.....	181
10.2	Superframe structure.....	181
10.2.1	Overview of superframe structure	181
10.2.2	Channel access	181
10.2.3	Starting and realigning a PAN	184
10.2.4	Beacon generation.....	186
10.2.5	Realignment in a PAN	187
10.2.6	Synchronization with beacons	187
10.2.7	Transmission when using superframe structure.....	189
10.2.8	Header IEs for superframe structure	189
10.2.9	Primitives for updating the superframe configuration	190
10.2.10	Primitives for synchronizing with a coordinator	193
10.2.11	MAC constants and PIB attributes for superframe structure	195
10.3	Timeslotted channel hopping (TSCH).....	196
10.3.1	Overview of TSCH	196
10.3.2	Channel access for TSCH	196
10.3.3	Starting and maintaining PANs	201
10.3.4	Association and disassociation for TSCH	202
10.3.5	Synchronization in TSCH PAN.....	202
10.3.6	Transmission	205
10.3.7	Reception in TSCH	205
10.3.8	Header IEs for TSCH.....	206
10.3.9	Nested IEs for TSCH	206
10.3.10	MAC management service primitives for TSCH	209
10.3.11	MAC constants and PIB attributes for TSCH.....	216
10.4	Deterministic and synchronous multichannel extension (DSME).....	219
10.4.1	DSME multi-superframe structure.....	219
10.4.2	DSME command requirements.....	220
10.4.3	DSME multi-superframe structure.....	220
10.4.4	Channel diversity	221
10.4.5	CAP reduction.....	224
10.4.6	DSME GTS allocation and management	225
10.4.7	Beacon scheduling	231
10.4.8	Time synchronization	232
10.4.9	Deferred beacon	233
10.4.10	Passive channel scan	233
10.4.11	Header IEs for DSME	233
10.4.12	MAC commands for DSME	237

10.4.13	MAC management service primitives for DSME.....	248
10.4.14	MAC constants and PIB attributes for DSME.....	257
10.5	Low energy (LE) using coordinated sampled listening (CSL)	260
10.5.1	Overview of LE and CSL	260
10.5.2	LE functional description.....	260
10.5.3	LE transmission, reception, and acknowledgment with positive handshakes	261
10.5.4	Coordinated sampled listening (CSL).....	261
10.5.5	Header IEs for CSL.....	265
10.5.6	Nested IEs for CSL	266
10.5.7	MAC constants and PIB attributes for LE and CSL	266
10.6	Receiver initiated transmission (RIT).....	267
10.6.1	Overview of RIT	267
10.6.2	Starting and maintaining PANs	267
10.6.3	Reception and transmission	268
10.6.4	Implicit receiver initiated transmission (I-RIT).....	273
10.6.5	Header IEs for RIT	273
10.6.6	MAC commands for RIT	273
10.6.7	MAC management service primitives for RIT	275
10.6.8	MAC constants and PIB attributes for RIT	279
10.7	Television white space (TVWS).....	280
10.7.1	General.....	280
10.7.2	Channel timing management (CTM).....	281
10.7.3	Nested IEs for TVWS	282
10.7.4	MAC constants and PIB attributes for TVWS.....	296
10.8	TVWS multichannel cluster tree PAN (TMCTP).....	296
10.8.1	Overview of TMCTP	296
10.8.2	Superframe use for TMCTP operation	298
10.8.3	Starting and maintaining TMCTPs	299
10.8.4	Nested IEs for TMCTP	302
10.8.5	MAC commands for TMCTP	303
10.8.6	MAC management service primitives for TMCTP	305
10.8.7	MAC constants and PIB attributes for TMCTP.....	308
10.9	Multi-PHY management (MPM).....	309
10.9.1	Overview of MPM	309
10.9.2	Channel access: Enhanced Beacon frame timing for MPM procedure	309
10.9.3	MPM procedure for inter-PHY coexistence	310
10.9.4	Nested IEs for MPM	312
10.9.5	MAC constants and PIB attributes for MPM.....	313
10.10	Priority channel access (PCA)	313
10.10.1	Overview of PCA.....	313
10.10.2	Channel access when using PCA	313
10.10.3	Nested IEs for PCA.....	317
10.10.4	MAC constants and PIB attributes for PCA	317
10.11	Slotted CSMA-CA algorithm	318
10.12	Suspendable CSMA-CA algorithm	320
10.12.1	Overview of suspendable CSMA-CA algorithm	320
10.12.2	Channel access when using suspendable CSMA-CA algorithm	320
10.12.3	MAC constants and PIB attributes for suspendable CSMA-CA algorithm.....	320
10.13	Rail communications and control network (RCCN).....	321
10.13.1	Overview of RCCN	321
10.13.2	Rail communications and control network (RCCN) superframe structure.....	321
10.13.3	Header IEs for RCCN	322
10.13.4	Nested IEs for RCCN	325
10.13.5	MAC constants and PIB attributes for RCCN	326

10.14	Smart utility network (SUN).....	327
10.14.1	Overview of SUN	327
10.14.2	Starting a PAN in SUN	327
10.14.3	Nested IEs for SUN	327
10.15	Low-energy, critical infrastructure monitoring (LECIM)	335
10.15.1	Overview of LECIM	335
10.15.2	Header IEs for LECIM	336
10.15.3	Nested IEs for LECIM.....	340
10.16	Channel hopping.....	345
10.16.1	Overview of channel hopping.....	345
10.16.2	Nested IEs for channel hopping.....	347
10.16.3	MAC constants and PIB attributes for channel hopping	348
10.17	PAN ID conflict resolution.....	348
10.17.1	General.....	348
10.17.2	Detection.....	349
10.17.3	Resolution	349
10.17.4	MAC commands for PAN ID conflict resolution.....	349
10.18	ED channel scan.....	350
10.19	Active and enhanced active channel scan.....	350
10.20	Orphan channel scan	352
10.20.1	Overview of orphan channel scan.....	352
10.20.2	Channel access	352
10.20.3	MAC commands for orphan channel scan.....	353
10.20.4	MAC management service primitives for orphan channel scan	354
10.21	Association and disassociation	355
10.21.1	Overview of association and disassociation	355
10.21.2	Association.....	355
10.21.3	Disassociation	359
10.21.4	Fast association	360
10.21.5	MAC commands for association and disassociation	361
10.21.6	MAC management service primitives for association and disassociation.....	364
10.21.7	MAC constants and PIB attributes for association and disassociation	372
10.22	Extracting pending data from a coordinator	373
10.22.1	Overview.....	373
10.22.2	Transaction handling.....	373
10.22.3	Extracting pending data from a coordinator	374
10.22.4	MAC commands for extracting pending data from a coordinator	376
10.22.5	MAC management service primitives for extracting pending data from a coordinator	377
10.23	Promiscuous mode	378
10.23.1	Overview of promiscuous mode	378
10.23.2	MAC constants and PIB attributes for promiscuous mode.....	379
10.24	Device Announcement (DA)	379
10.24.1	Overview.....	379
10.24.2	Header IEs for DA	380
10.24.3	MAC management service primitives for DA	380
10.25	Guaranteed timeslot (GTS).....	382
10.25.1	GTS general requirements	382
10.25.2	CAP maintenance	383
10.25.3	GTS allocation	383
10.25.4	GTS usage	385
10.25.5	GTS deallocation	385
10.25.6	GTS reallocation	387
10.25.7	GTS expiration.....	388

10.25.8	Header IEs for GTS	388
10.25.9	MAC commands for GTS.....	389
10.25.10	MAC management service primitives for GTS	389
10.25.11	MAC constants and PIB attributes for GTS	391
10.26	PHY parameters change notification procedure	392
10.26.1	Signaling using Beacon frames.....	392
10.26.2	Signaling using multipurpose frames	392
10.26.3	Nested IEs for PHY parameters change	393
10.26.4	MAC management service primitives for PHY parameters change.....	395
10.27	MAC metrics.....	399
10.27.1	Overview of MAC metrics	399
10.27.2	Nested IEs for MAC metrics	399
10.27.3	MAC constants and PIB attributes for MAC metrics	400
10.28	Spectrum resource measurement (SRM)	401
10.28.1	General.....	401
10.28.2	SRM performance metrics	402
10.28.3	SRM functionality.....	407
10.28.4	Using Link Margin IE.....	410
10.28.5	Header IEs for SRM	410
10.28.6	Nested IEs for SRM	412
10.28.7	MAC commands for SRM.....	412
10.28.8	MAC management service primitives for SRM	416
10.28.9	MAC constants and PIB attributes for SRM	430
10.29	Ranging.....	432
10.29.1	Ranging measurements	432
10.29.2	Set-up activities before a ranging exchange	440
10.29.3	Finish-up activities after a ranging exchange	440
10.29.4	Managing DPS and dynamic channel selection (DCS)	440
10.29.5	The basic ranging exchange.....	442
10.29.6	Ranging procedures	443
10.29.7	Header IEs for ranging.....	450
10.29.8	Nested IEs for ranging	450
10.29.9	MAC management service primitives for ranging	458
10.29.10	MAC constants and PIB attributes for ranging.....	465
10.30	Ranging: Ranging in a PAN using superframe structure with ERDEV	465
10.30.1	Overview.....	465
10.30.2	Nested IEs when doing ranging in a PAN using superframe structure with ERDEV	466
10.31	Ranging: Secure transactions.....	467
10.32	Ranging: Multi-node ranging.....	469
10.32.1	Introduction.....	469
10.32.2	Ranging block and round structure	470
10.32.3	Ranging modes	473
10.32.4	Ranging procedure for one-to-many SS-TWR	482
10.32.5	Ranging procedure for one-to-many DS-TWR	483
10.32.6	Ranging procedure for many-to-many SS-TWR.....	486
10.32.7	Ranging procedure for many-to-many DS-TWR	487
10.32.8	Ranging procedures with SP3 format packets	489
10.32.9	Nested IEs for multi-node ranging.....	491
10.33	Ranging: Authenticated challenge-response ranging	501
10.33.1	Overview of ACRR	501
10.33.2	Reception while doing ACRR	503
10.33.3	Security levels.....	503
10.33.4	Coordinating ranging methods and security levels.....	505

10.33.5	ACRR procedures	505
10.33.6	Nested IEs for ACRR	514
10.33.7	MAC commands for ACRR	515
10.33.8	MAC management service primitives for ACRR	517
10.34	Ranging: Ranging message non-receipt exchange	525
10.34.1	Overview.....	525
10.34.2	Nested IEs for ranging message non-receipt exchange	526
10.35	Ranging ancillary information	526
10.35.1	Overview.....	526
10.35.2	Nested IEs for ranging ancillary information	527
10.36	Ranging: Multiple message receipt confirmation.....	527
10.36.1	Overview.....	527
10.36.2	Nested IEs for ranging ancillary information	528
10.37	Timeslot relaying based link extension (TRLE).....	529
10.37.1	General.....	529
10.37.2	Link extension for a PAN using superframe structure	530
10.37.3	Link extension for the non-TRLE PAN.....	530
10.37.4	Link extension for the TRLE-enabled PAN	532
10.37.5	MAC services for the TRLE-enabled PAN	540
11.	General PHY requirements	554
11.1	General.....	554
11.1.1	Requirements and definitions	554
11.1.2	Operating frequency range.....	555
11.1.3	Channel assignments.....	564
11.1.4	Minimum LIFS and SIFS periods.....	592
11.1.5	RF power measurement	592
11.1.6	Transmit power	592
11.1.7	Out-of-band spurious emission	592
11.1.8	Receiver sensitivity definitions.....	592
11.1.9	Common signaling mode (CSM) for SUN PHY	593
11.2	General radio specifications.....	593
11.2.1	General.....	593
11.2.2	TX-to-RX turnaround time	593
11.2.3	RX-to-TX turnaround time	594
11.2.4	Error-vector magnitude (EVM) definition.....	594
11.2.5	Receiver maximum input level of desired signal.....	595
11.2.6	Receiver ED	595
11.2.7	Link quality indicator (LQI)	595
11.2.8	Clear channel assessment (CCA).....	595
11.3	Ranging capable PHY	596
11.3.1	General.....	596
11.3.2	Distance commitment on PSDU	596
12.	PHY services	599
12.1	Overview.....	599
12.2	PHY constants.....	599
12.3	PHY PIB attributes	600
12.3.1	Overview.....	600
12.3.2	Generic PHY PIB attributes.....	600
12.3.3	Generic LECIM PHY related PIB attributes	602
12.3.4	LECIM DSSS related PIB attributes	603

12.3.5	LECIM FSK related PIB attributes.....	603
12.3.6	LRP UWB related PIB attributes.....	604
12.3.7	HRP UWB related PIB attributes	605
12.3.8	TVWS related PIB attributes	609
12.3.9	RS-GFSK related PIB attributes	609
12.3.10	FSK related PIB attributes	610
12.3.11	SUN FSK PHY related PIB attributes	610
12.3.12	Other PHY related PIB attributes	611
13.	O-QPSK PHY	613
13.1	PPDU format.....	613
13.1.1	General.....	613
13.1.2	SHR field format.....	613
13.1.3	PHR field format.....	613
13.2	Modulation and spreading	614
13.2.1	General.....	614
13.2.2	Data rate	614
13.2.3	Reference modulator diagram.....	614
13.2.4	Bit-to-symbol mapping	614
13.2.5	Symbol-to-chip mapping	615
13.2.6	O-QPSK modulation.....	616
13.2.7	Pulse shape.....	616
13.2.8	Chip transmission order	617
13.3	O-QPSK PHY RF requirements	617
13.3.1	Operating frequency range.....	617
13.3.2	Transmit power spectral density (PSD) mask.....	618
13.3.3	Symbol rate	618
13.3.4	Receiver sensitivity	618
13.3.5	Receiver interference rejection	618
13.3.6	TX-to-RX turnaround time	619
13.3.7	RX-to-TX turnaround time	619
13.3.8	EVM.....	619
13.3.9	Transmit center frequency tolerance.....	619
13.3.10	Transmit power	619
13.3.11	Receiver maximum input level of desired signal.....	619
13.3.12	Receiver ED	619
13.3.13	LQI.....	619
14.	Binary phase-shift keying (BPSK) PHY	620
14.1	PPDU format.....	620
14.2	Modulation and spreading	620
14.2.1	General.....	620
14.2.2	BPSK PHY data rates	620
14.2.3	Reference modulator.....	620
14.2.4	Differential encoding	620
14.2.5	Bit-to-chip mapping	621
14.2.6	BPSK modulation	621
14.3	BPSK PHY RF requirements	621
14.3.1	Operating frequency range.....	621
14.3.2	915 MHz band transmit PSD mask.....	621
14.3.3	Symbol rate	622
14.3.4	Receiver sensitivity	622

14.3.5	Receiver interference rejection	622
14.3.6	TX-to-RX turnaround time	622
14.3.7	RX-to-TX turnaround time	623
14.3.8	EVM.....	623
14.3.9	Transmit center frequency tolerance.....	623
14.3.10	Transmit power.....	623
14.3.11	Receiver maximum input level of desired signal.....	623
14.3.12	Receiver ED	623
14.3.13	LQI.....	623
15.	Chirp spread spectrum (CSS) PHY	624
15.1	CSS PPDU format	624
15.1.1	General.....	624
15.1.2	Preamble field	624
15.1.3	SFD field.....	624
15.1.4	PHR field	625
15.1.5	PHY Payload field	625
15.2	Modulation and spreading	625
15.2.1	General.....	625
15.2.2	Data rates	625
15.2.3	Reference modulator.....	625
15.2.4	De-multiplexer (DEMUX).....	626
15.2.5	Serial-to-parallel mapping	626
15.2.6	Data-symbol-to-bi-orthogonal-codeword mapping	626
15.2.7	Parallel-to-serial converter and QPSK symbol mapping.....	630
15.2.8	DQPSK coding	630
15.2.9	DQPSK-to-DQCSK modulation.....	631
15.2.10	CSK generator.....	631
15.2.11	Bit interleaver	631
15.3	Waveform and subchirp sequences.....	631
15.3.1	General.....	631
15.3.2	Graphical presentation of chirp symbols (subchirp sequences).....	632
15.3.3	Active usage of time gaps.....	632
15.3.4	Mathematical representation of the continuous time CSS base-band signal	633
15.3.5	Raised cosine window for chirp pulse shaping.....	635
15.3.6	Subchirp transmission order	635
15.3.7	Example of CSK signal generation.....	636
15.4	CSS RF requirements.....	637
15.4.1	General.....	637
15.4.2	Transmit power spectral density (PSD) mask and signal tolerance.....	637
15.4.3	Symbol rate	638
15.4.4	Receiver sensitivity	638
15.4.5	Receiver interference rejection	638
15.4.6	TX-to-RX turnaround time	638
15.4.7	RX-to-TX turnaround time	638
15.4.8	Transmit center frequency tolerance.....	639
15.4.9	Transmit power	639
15.4.10	Receiver maximum input level of desired signal.....	639
15.4.11	Receiver ED	639
15.4.12	LQI.....	639
16.	HRP UWB PHY	640

16.1	General.....	640
16.2	HRP UWB PPDU format	641
16.2.1	General.....	641
16.2.2	PPDU encoding process.....	642
16.2.3	Symbol structure	644
16.2.4	PSDU timing parameters	645
16.2.5	Preamble timing parameters	647
16.2.6	SHR field	649
16.2.7	PHR field	654
16.2.8	PHY Payload field	657
16.2.9	Scrambled timestamp sequence (STS) field	658
16.3	Modulation.....	661
16.3.1	Modulation mathematical framework.....	661
16.3.2	Spreading	662
16.3.3	FEC	664
16.3.4	HRP-ERDEV modulation in HPRF mode	666
16.4	RF requirements.....	670
16.4.1	Operating frequency bands	670
16.4.2	Channel assignments.....	671
16.4.3	Regulatory compliance	671
16.4.4	Baseband impulse response	671
16.4.5	Transmit PSD mask	674
16.4.6	Chip rate clock and chip carrier alignment.....	674
16.4.7	TX-to-RX turnaround time	675
16.4.8	RX-to-TX turnaround time	675
16.4.9	Transmit center frequency tolerance.....	675
16.4.10	Receiver maximum input level of desired signal.....	675
16.4.11	Receiver ED	675
16.4.12	LQI.....	675
16.4.13	CCA	675
16.5	HRP UWB PHY optional pulse shapes	675
16.5.1	Overview.....	675
16.5.2	HRP UWB PHY optional chirp on UWB (CoU) pulses	676
16.5.3	HRP UWB PHY optional continuous spectrum (CS) pulses	677
16.5.4	HRP UWB PHY linear combination of pulses (LCP).....	678
16.6	Extended preamble for optional CCA mode 6.....	679
16.7	HRP-ERDEV parameter sets	680
17.	GFSK PHY	683
17.1	PPDU formats	683
17.2	Modulation.....	683
17.2.1	GFSK PHY data rates	683
17.2.2	Reference modulator diagram.....	683
17.2.3	Data whitening	683
17.2.4	GFSK modulation	684
17.3	GFSK PHY RF requirements	684
17.3.1	Operating frequency range.....	684
17.3.2	Transmit PSD mask	684
17.3.3	Symbol rate	685
17.3.4	Receiver sensitivity	685
17.3.5	Receiver interference rejection	685
17.3.6	TX-to-RX turnaround time	685
17.3.7	RX-to-TX turnaround time	685

17.3.8	Transmit center frequency tolerance.....	685
17.3.9	Transmit power	685
17.3.10	Receiver maximum input level of desired signal.....	685
17.3.11	Receiver ED	686
17.3.12	LQI.....	686
18.	MSK PHY.....	687
18.1	PPDU formats	687
18.1.1	Overview.....	687
18.1.2	Frame Length LSB field	687
18.1.3	Extended PHR field	687
18.1.4	Frame Length MSB field	687
18.2	Data rate.....	688
18.3	Multi-PHY functionality.....	688
18.4	SFD for the MSK PHY	688
18.5	MSK modulation.....	689
18.5.1	Reference modulator diagram.....	689
18.5.2	Data whitening	689
18.5.3	Bit-to-symbol mapping	689
18.5.4	Signal modulation	689
18.6	MSK PHY requirements	690
18.6.1	Operating frequency range.....	690
18.6.2	Transmit PSD mask	690
18.6.3	Symbol rate	690
18.6.4	Transmit center frequency tolerance.....	691
18.6.5	Transmit power	691
18.6.6	Receiver maximum input level of desired signal.....	691
18.6.7	Modulation frequency deviation tolerance	691
18.6.8	Zero crossing tolerance	691
19.	LRP UWB PHY specification	692
19.1	Overview.....	692
19.2	LRP UWB PHY symbol structure	693
19.2.1	Overview.....	693
19.2.2	Base mode LRP UWB PHY symbol structure	694
19.2.3	Extended mode LRP UWB PHY symbol structure	694
19.2.4	Long-range mode LRP UWB PHY symbol structure	696
19.2.5	Dual-frequency LRP UWB PHY symbol structure	697
19.2.6	Variable pulse repetition period (PRP).....	697
19.3	LRP UWB SHR	698
19.3.1	General.....	698
19.3.2	LRP UWB SHR preamble	698
19.3.3	LRP UWB SHR SFD.....	699
19.4	LRP UWB PHR.....	700
19.4.1	General.....	700
19.4.2	Encoding Type field.....	700
19.4.3	Header Extension field.....	701
19.4.4	SECDED field.....	701
19.4.5	Frame Length field.....	701
19.4.6	Location enhancing information postamble (LEIP) Length field.....	701
19.4.7	LEIP Position field.....	702
19.5	LRP UWB PSDU.....	702

19.5.1	General.....	702
19.5.2	PSDU in enhanced payload capacity (EPC) mode	703
19.6	LRP UWB location enhancing information postamble	704
19.7	LRP UWB transmitter specification	705
19.7.1	Pulse shape.....	705
19.7.2	Pulse timing	705
19.7.3	Transmit PSD mask	705
19.8	LRP UWB transmit and receive timing requirements	710
19.8.1	Fixed reply time	710
19.8.2	Turnaround times	710
20.	SUN FSK PHY	711
20.1	Introduction.....	711
20.2	PPDU format for SUN FSK.....	712
20.2.1	General.....	712
20.2.2	SHR field format.....	712
20.2.3	PHR field format.....	713
20.2.4	Mode Switch PHR	713
20.2.5	PHY Payload field	716
20.3	Modulation and coding for SUN FSK	716
20.3.1	General.....	716
20.3.2	Reference modulator.....	720
20.3.3	Bit-to-symbol mapping	721
20.3.4	Modulation quality.....	721
20.3.5	FEC	723
20.3.6	Code-symbol interleaving.....	726
20.4	Data whitening for SUN FSK.....	727
20.5	Mode switch mechanism for SUN FSK	727
20.6	SUN FSK PHY RF requirements	730
20.6.1	Operating frequency range.....	730
20.6.2	Regulatory compliance	730
20.6.3	Radio frequency tolerance	730
20.6.4	Channel switch time.....	730
20.6.5	Transmitter symbol rate	730
20.6.6	Transmit spectral mask	731
20.6.7	Receiver sensitivity.....	732
20.6.8	Receiver interference rejection	732
20.6.9	TX-to-RX turnaround time	732
20.6.10	RX-to-TX turnaround time	732
20.6.11	Transmit power.....	732
20.6.12	Receiver maximum input level of desired signal.....	733
20.6.13	Receiver ED	733
20.6.14	LQI.....	733
21.	SUN OFDM PHY	734
21.1	Introduction.....	734
21.2	PPDU format for SUN OFDM	734
21.2.1	General.....	734
21.2.2	Short Training field (STF)	734
21.2.3	Long Training field (LTf)	738
21.2.4	PHR.....	741
21.2.5	PSDU field	743

21.3	Data rates for SUN OFDM	743
21.4	Modulation and coding for SUN OFDM	744
21.4.1	Reference modulator diagram.....	744
21.4.2	Bit-to-symbol mapping	744
21.4.3	PIB attribute values for phySymbolsPerOctet	745
21.4.4	FEC	745
21.4.5	Interleaver	746
21.4.6	Frequency spreading	748
21.4.7	Pilot tones/null tones.....	749
21.4.8	Cyclic prefix (CP).....	752
21.4.9	PPDU Tail field	752
21.4.10	Pad field	752
21.4.11	Scrambler and scrambler seeds.....	753
21.5	SUN OFDM PHY RF requirements	754
21.5.1	Operating frequency range.....	754
21.5.2	Transmit power spectral density (PSD) mask.....	754
21.5.3	Receiver sensitivity	755
21.5.4	Adjacent channel rejection.....	755
21.5.5	Alternate channel rejection	756
21.5.6	TX-to-RX turnaround time	756
21.5.7	RX-to-TX turnaround time	756
21.5.8	EVM definition	756
21.5.9	Transmit center frequency and symbol tolerance	757
21.5.10	Transmit power	757
21.5.11	Receiver maximum input level of desired signal.....	757
21.5.12	Receiver ED	758
21.5.13	LQI.....	758
21.5.14	Cca	758
22.	SUN O-QPSK PHY	759
22.1	Introduction.....	759
22.2	PPDU format for SUN O-QPSK	759
22.2.1	General.....	759
22.2.2	SHR field format.....	759
22.2.3	PHR field format.....	760
22.2.4	PHY Payload field	761
22.3	Modulation and coding for SUN O-QPSK	761
22.3.1	Reference modulator.....	761
22.3.2	SHR coding and spreading	762
22.3.3	PHR coding and spreading	763
22.3.4	PSDU coding and spreading for DSSS.....	764
22.3.5	PSDU coding and spreading for MDSSS	768
22.3.6	FEC	770
22.3.7	Code-bit interleaving	772
22.3.8	Bit differential encoding (BDE)	773
22.3.9	DSSS bit-to-chip mapping	774
22.3.10	MDSSS bit-to-chip mapping	778
22.3.11	Chip whitening.....	781
22.3.12	Pilot insertion	783
22.3.13	Modulation parameters for O-QPSK	785
22.4	Support of legacy devices of the 780 MHz, 915 MHz, and 2450 MHz O-QPSK PHYs	786
22.5	SUN O-QPSK PHY RF requirements	786
22.5.1	Operating frequency range.....	786

22.5.2	Transmit power spectral density (PSD) mask.....	787
22.5.3	Receiver sensitivity.....	787
22.5.4	Adjacent channel rejection.....	789
22.5.5	TX-to-RX turnaround time	791
22.5.6	RX-to-TX turnaround time	791
22.5.7	EVM definition	791
22.5.8	Transmit center frequency and symbol tolerance	791
22.5.9	Transmit power.....	791
22.5.10	Receiver maximum input level of desired signal.....	791
22.5.11	Receiver ED	791
22.5.12	LQI.....	791
22.5.13	CCA	791
23.	LECIM DSSS PHYs	793
23.1	PPDU format for DSSS	793
23.2	Modulation and spreading	793
23.2.1	General.....	793
23.2.2	Data rate.....	793
23.2.3	Reference modulator diagram.....	794
23.2.4	Convolutional FEC encoding.....	794
23.2.5	Interleaver	795
23.2.6	Differential encoding	796
23.2.7	Bit-to-symbol and symbol-to-chip encoding	797
23.2.8	BPSK/O-QPSK modulation.....	801
23.3	PSDU fragmentation.....	801
23.3.1	General.....	801
23.3.2	Configuration	802
23.3.3	Fragmentation	802
23.3.4	Fragment packet.....	803
23.3.5	Calculating FICS field using MIC	803
23.3.6	Fragment acknowledgment and retransmission.....	804
23.3.7	Frak	804
23.3.8	Reassembly	806
23.4	DSSS PHY RF requirements	806
23.4.1	Radio frequency tolerance	806
23.4.2	Channel switch time.....	806
23.4.3	Transmit spectral mask	806
23.4.4	Receiver sensitivity.....	807
23.4.5	Receiver interference rejection	807
23.4.6	TX-to-RX turnaround time	808
23.4.7	RX-to-TX turnaround time	808
23.4.8	Transmit power	808
24.	LECIM FSK PHY specification	809
24.1	Introduction.....	809
24.2	General.....	809
24.3	PPDU format for LECIM FSK PHY	810
24.3.1	General.....	810
24.3.2	SHR field format.....	810
24.3.3	PHR field format.....	811
24.3.4	PHY Payload field	811
24.3.5	Radio-burst format for split mode	811

24.4	Modulation and coding for LECIM FSK PHY	812
24.4.1	General.....	812
24.4.2	Reference modulator.....	813
24.4.3	Bit-to-symbol mapping.....	814
24.4.4	Modulation quality.....	815
24.4.5	FEC	816
24.4.6	Code-bit interleaving for non-split mode.....	820
24.4.7	Codeword splitting and interleaving for split mode	821
24.4.8	Radio-burst transmit time and channel selection.....	824
24.4.9	Precoding	826
24.4.10	Spreading	826
24.5	Data whitening for LECIM FSK PHY	827
24.6	PSDU fragmentation.....	828
24.7	LECIM FSK PHY RF requirements	828
24.7.1	Operating frequency range.....	828
24.7.2	Radio frequency tolerance	828
24.7.3	Channel switch time.....	829
24.7.4	Transmit spectral mask	829
24.7.5	Receiver sensitivity.....	829
24.7.6	TX-to-RX turnaround time	829
24.7.7	RX-to-TX turnaround time	829
24.7.8	Transmit power	829
24.7.9	CCA	829
25.	TVWS-FSK PHY	830
25.1	PPDU format for TVWS-FSK	830
25.1.1	General.....	830
25.1.2	SHR field format.....	830
25.1.3	PHR field format.....	831
25.1.4	PHY Payload field	831
25.2	Modulation and coding for TVWS-FSK	831
25.2.1	General.....	831
25.2.2	Reference modulator.....	832
25.2.3	FEC and interleaving	832
25.2.4	Data whitening	833
25.2.5	Spreading	833
25.2.6	Bit-to-symbol mapping	833
25.2.7	Modulation quality.....	833
25.2.8	Values for phySymbolsPerOctet.....	834
25.3	TVWS-FSK RF requirements.....	834
25.3.1	Operating frequency range.....	834
25.3.2	Clock frequency and timing accuracy	834
25.3.3	Channel switch time.....	834
25.3.4	Receiver sensitivity.....	834
25.3.5	TX-to-RX turnaround time	834
25.3.6	RX-to-TX turnaround time	834
25.3.7	Receiver maximum input level of desired signal.....	834
25.3.8	Receiver ED	834
25.3.9	LQI.....	834
26.	TVWS-OFDM PHY	835
26.1	General.....	835

26.2	PPDU format for TVWS-OFDM.....	835
26.2.1	General.....	835
26.2.2	STF.....	835
26.2.3	LTF	837
26.2.4	PHR field format.....	839
26.2.5	PSDU field.....	839
26.3	System parameters for TVWS-OFDM	839
26.4	Modulation and coding for TVWS-OFDM	840
26.4.1	Reference modulator.....	840
26.4.2	Bit-to-symbol mapping	841
26.4.3	FEC	842
26.4.4	Interleaver	842
26.4.5	Pilot tones/null tones.....	844
26.4.6	CP.....	845
26.4.7	PPDU Tail field	845
26.4.8	Pad field	845
26.4.9	Scrambler and scrambler seeds.....	845
26.5	TVWS-OFDM RF requirements	845
26.5.1	Operating frequency range.....	845
26.5.2	Pulse shaping	846
26.5.3	Transmit power spectral density (PSD) mask.....	846
26.5.4	Receiver sensitivity.....	846
26.5.5	TX-to-RX turnaround time	846
26.5.6	RX-to-TX turnaround time	846
26.5.7	EVM definition	846
26.5.8	Transmit center frequency and symbol tolerance	847
27.	TVWS-NB-OFDM PHY	848
27.1	PPDU format for TVWS-NB-OFDM.....	848
27.1.1	General.....	848
27.1.2	Short Training field (STF)	848
27.1.3	Long training field (LTF)	852
27.1.4	PHR.....	856
27.1.5	PHY Payload field	857
27.2	System parameters for TVWS-NB-OFDM	857
27.3	Modulation and coding parameters for TVWS-NB-OFDM.....	858
27.3.1	General.....	858
27.3.2	Reference modulator.....	858
27.3.3	Scrambler and scrambler seed	858
27.3.4	Outer encoding.....	858
27.3.5	Inner encoding	859
27.3.6	Pad bit insertion	862
27.3.7	Spreader	862
27.3.8	Bit interleaving	863
27.3.9	Subcarrier mapping.....	863
27.3.10	Frequency interleaving	865
27.3.11	Pilot tones	866
27.3.12	Cyclic prefix	866
27.3.13	Pulse shaping	866
27.3.14	PIB attribute values for phySymbolsPerOctet	867
27.4	Channel aggregation for TVWS-NB-OFDM	867
27.5	TVWS-NB-OFDM RF requirements.....	867
27.5.1	Operating frequency range.....	867

27.5.2	Receiver sensitivity.....	867
27.5.3	TX-to-RX turnaround time	868
27.5.4	RX-to-TX turnaround time	868
27.5.5	EVM definition	868
27.5.6	Transmit center frequency and symbol tolerance	869
28.	RCC LMR PHY.....	870
28.1	RCC PHY overview.....	870
28.2	PPDU format.....	870
28.2.1	General.....	870
28.2.2	SHR.....	870
28.2.3	PHR.....	871
28.2.4	PHY payload.....	871
28.2.5	Tail bits	871
28.3	FEC	871
28.4	Interleaver	872
28.5	Data whitening.....	872
28.6	Modulation.....	873
28.6.1	GMSK.....	873
28.6.2	4-FSK.....	873
28.6.3	QPSK	874
28.6.4	$\pi/4$ DQPSK.....	875
28.6.5	DSSS DPSK.....	875
28.7	Reference modulator.....	877
28.8	LMR PHY RF requirements.....	877
28.8.1	Transmitter symbol rate tolerance	877
28.8.2	Channel switching time	877
28.8.3	Error vector magnitude	877
28.8.4	Receiver sensitivity.....	878
28.8.5	Receiver interference rejection	878
28.8.6	Receiver maximum input level of desired signal.....	878
28.8.7	TX-to-RX turnaround time	878
28.8.8	RX-to-TX turnaround time	878
28.8.9	Receiver ED	878
28.8.10	LQI.....	878
29.	RCC DSSS BPSK PHY	879
29.1	Overview.....	879
29.2	RCC DSSS BPSK PHY specification	879
30.	CMB PHY.....	880
30.1	CMB O-QPSK PHY specification.....	880
30.1.1	PPDU format for the CMB O-QPSK PHY	880
30.1.2	Modulation and coding for CMB O-QPSK PHY	881
30.1.3	CMB O-QPSK PHY RF requirements	882
30.2	CMB GFSK PHY specification.....	884
30.2.1	PPDU format for CMB GFSK PHY	884
30.2.2	Modulation and coding for CMB GFSK PHY	885
30.2.3	Data whitening for CMB GFSK PHY	887
30.2.4	CMB GFSK PHY RF requirements.....	888

31. TASK PHY	890
31.1 General.....	890
31.2 PPDU	890
31.2.1 General.....	890
31.2.2 PPDU format.....	890
31.2.3 Generation of PPDU signal.....	893
31.3 MCS mode, MCS, data rates, and related parameters	894
31.3.1 MCS mode	894
31.3.2 Data rates in the 2450 MHz band	894
31.3.3 Data rates in the 780 MHz, 863 MHz, and 915 MHz bands.....	895
31.3.4 Data rates in the 433 MHz and 470 MHz bands.....	895
31.4 FEC, ternary sequence spreading, and pseudo-random chip inversion	896
31.4.1 General.....	896
31.4.2 FEC codes	897
31.4.3 Ternary sequence spreading: Data-symbol-to-chip conversion.....	902
31.4.4 Pseudo-random chip inversion.....	904
31.5 Modulation.....	906
31.6 Pulse shaping	907
31.7 Representation of the modulated waveforms.....	907
31.8 RF requirements.....	907
31.8.1 Transmit PSD mask	907
31.8.2 Receiver sensitivity	908
31.8.3 Interference rejection capability	908
31.8.4 TX-to-RX turnaround time	909
31.8.5 RX-to-TX turnaround time	909
31.8.6 EVM.....	909
31.8.7 Transmit power	909
31.8.8 Transmit center frequency tolerance.....	909
31.8.9 Receiver maximum input level of desired signal.....	909
31.8.10 Receiver ED	909
31.8.11 SNR measurement	909
31.8.12 CCA	909
32. RS-GFSK PHY	910
32.1 PPDU format.....	910
32.1.1 General.....	910
32.1.2 Preamble field	910
32.1.3 SFD	910
32.1.4 Long PHR	910
32.1.5 Short PHR	911
32.2 Modulation and coding	912
32.2.1 General.....	912
32.2.2 Reference modulator diagram.....	913
32.2.3 Differential encoding	913
32.2.4 Bit-to-symbol mapping	914
32.2.5 Modulation quality	914
32.2.6 Frequency deviation tolerance	914
32.2.7 Zero crossing tolerance	915
32.2.8 FEC	915
32.2.9 Code-symbol interleaving	915
32.2.10 Data whitening for RS-GFSK	915
32.3 Rate switch RS-GFSK	916

32.4	RF requirements.....	916
32.4.1	RF tolerance	916
32.4.2	Channel switch time.....	916
32.4.3	Receiver sensitivity.....	916
32.4.4	Receiver interference rejection	917
32.4.5	TX-to-RX turnaround time	917
32.4.6	RX-to-TX turnaround time	917
32.4.7	Receiver maximum input level of desired signal.....	917
32.4.8	Receiver ED.....	917
32.4.9	LQI.....	917
32.4.10	CCA	917
	Annex A (informative) Bibliography	918
	Annex B (normative) CCM* and CCM mode of operation	921
B.1	Introduction.....	921
B.2	Symmetric-key cryptographic building blocks.....	921
B.2.1	General	921
B.2.2	Block cipher	921
B.2.3	Mode of operation	921
B.3	Specification of generic CCM* and CCM modes of operation.....	922
B.3.1	Prerequisites	922
B.3.2	CCM* and CCM modes encryption and authentication transformation.....	922
B.3.3	CCM* and CCM modes decryption and authentication checking transformations	924
B.3.4	Restrictions.....	925
	Annex C (informative) Test vectors for cryptographic building blocks.....	927
C.1	General.....	927
C.2	AES block cipher	927
C.3	Mode of operation.....	927
C.3.1	General	927
C.3.2	MAC beacon frame	927
C.3.3	MAC command	931
C.4	Security processing operation	936
C.4.1	Beacon frame.....	936
C.4.2	MAC Command frame.....	936
C.4.3	MAC Command frame.....	936
C.4.4	MAC Command frame.....	937
C.4.5	Enhanced Beacon frame.....	937
C.4.6	Data frame	938
C.4.7	Ack frame	938
	Annex D (informative) AEAD algorithm support.....	939
	Annex E (informative) Protocol implementation conformance statement (PICS) proforma	940
E.1	Introduction.....	940
E.1.1	General	940
E.1.2	Scope	940
E.1.3	Purpose	940
E.2	Abbreviations and special symbols.....	940

E.3	Instructions for completing the PICS proforma.....	941
E.4	Identification of the implementation.....	941
E.5	Identification of the protocol	943
E.6	Global statement of conformance	943
E.7	PICS proforma tables.....	943
E.7.1	General	943
E.7.2	Optional groups	943
E.7.3	Functional device types	944
E.7.4	Major capabilities for the PHY	944
E.7.5	Major capabilities for the MAC sublayer.....	950
Annex F (informative) Geographic regional frequency band details		962
Annex G (informative) STS generation.....		963
G.1	Introduction.....	963
G.2	Test vectors for STS generation.....	963
G.3	Resulting STS modulation	964
Annex H (informative) Channel assignment for SUN FSK operating mode #9, #10, #11, and #12 in 920 MHz band		965
H.1	Channel assignments.....	965

IEEE Standard for Low-Rate Wireless Networks

1. Overview

1.1 Scope

This standard defines the physical layer (PHY) and medium access control (MAC) sublayer specifications for low-data-rate wireless connectivity with fixed, portable, and moving devices with no battery or very limited battery consumption requirements. In addition, the standard provides modes that allow for precision ranging. PHYs are defined for devices operating in a variety of geographic regions.

1.2 Purpose

The standard provides for ultra low complexity, ultra low cost, ultra low power consumption, and low data rate wireless connectivity among inexpensive devices, especially targeting the communications requirements of what is now commonly referred to as the Internet of Things. In addition, some of the alternate PHYs provide precision ranging capability that is accurate to one meter. Multiple PHYs are defined to support a variety of frequency bands.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6, 7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

⁶ The word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁷ The word *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI X3.66-1979, Advanced Data Communication Control Procedures.⁸

Code of Federal Regulations, Title 47: Telecommunication, Part 90—Private Land Mobile Radio Services, Subpart S—Regulations Governing Licensing and Use of Frequencies in the 806–824, 851–869, 896–901, and 935–940 MHz Bands (47 CFR, Part 90, Subpart S).⁹

Code of Federal Regulations, Title 47: Telecommunication, Part 90—Private Land Mobile Radio Services, Subpart Y—Regulations Governing Licensing and Use of Frequencies in the 4940–4990 MHz Band (47 CFR, Part 90, Subpart Y).

FIPS Pub 197, Advanced Encryption Standard (AES).¹⁰

IEEE Std 802[®], IEEE Standard for Local and Metropolitan Area Networks: Overview and Architecture.^{11, 12}

IEEE Std 802.15.9TM, IEEE Standard for Transport of Key Management Protocol (KMP) Datagrams.

IETF RFC 6225, Dynamic Host Configuration Protocol Options for Coordinate-Based Location Configuration Information, 2011.¹³

ISO/IEC 7816-4:2013, Identification cards—Integrated circuit cards—Part 4: Organization, security and commands for interchange.¹⁴

ISO/IEC 7816-5:2004, Identification cards—Integrated circuit cards—Part 5: Registration of application providers.

JIS X 6319-4:2016, Specification of implementation for integrated circuit(s) cards—Part 4: High speed proximity cards.¹⁵

⁸ ANSI publications are available from the American National Standards Institute (<https://www.ansi.org/>)

⁹ CFR publications are available from the U.S. Government Publishing Office (<https://www.gpo.gov/>).

¹⁰ FIPS publications are available from the National Technical Information Service, U. S. Department of Commerce (<https://www.ntis.gov/>).

¹¹ IEEE publications are available from The Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>).

¹² The IEEE standards or products referred to in Clause 2 are trademarks owned by The Institute of Electrical and Electronics Engineers, Incorporated.

¹³ IETF RFCs are available from the Internet Engineering Task Force (<https://www.ietf.org/>).

¹⁴ ISO publications are available from the International Organization for Standardization (<https://www.iso.org/>) and the American National Standards Institute (<https://www.ansi.org/>).

¹⁵ JIS standards are available from The Japanese Standards Association (<https://www.jsa.or.jp/>).

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary* should be consulted for terms not defined in this clause.¹⁶

association: The service used to establish membership for a device in a network.

authentication tag: Information that allows the verification of authenticity of a message.

channel hopping: Periodically switching the channel using a sequence known to both sending and receiving devices where the entire frame is sent on a single channel.

channel offset: A number used in the channel calculation of a slotted channel hopping system to allow for different channels to be used in the same slot.

chirp: Linear frequency sweep.

coordinator: Any device capable of providing coordinator functions.

dependent device: A device that operates without direct Internet access to the television white space (TVWS) database and depends on another device for channel availability information.

encryption: The transformation of a message into a new representation so that privileged information is required to recover the original representation.

fragment: An individual contiguous subset of a MAC protocol data unit.

frame: The format of aggregated bits from a medium access control sublayer entity that are transmitted together in time.

group key: A key that is known only to the devices in the group.

independent device: A device that has direct access to the television white space (TVWS) database via the Internet.

key: Privileged information that is used, for example, to protect information from disclosure to, and/or undetectable modification by, parties that do not have access to this privileged information.

keying material: The combination of a key and associated security information (e.g., a nonce value).

link key: A key that is shared between precisely two devices.

mobile device: A device whose location in the network can change.

nonce: A nonrepeating value, such as an increasing counter, a sufficiently long random string, or a timestamp.

packet: The formatted, aggregated bits that are transmitted together in time across the physical medium.

¹⁶ The IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

payload: The contents of a data message that is being transmitted.

radio frequency identification (RFID): The use of electromagnetic or inductive coupling in the radio frequency (RF) portion of the spectrum to communicate to or from a tag through a variety of modulation and encoding schemes to uniquely read the identity of an RF tag.

scrambled timestamp sequence (STS): A sequence of pseudo-randomized pulses generated using a deterministic random bit generator (DRBG).

slotframe: A collection of timeslots repeating in time, analogous to a superframe in that it defines periods of communication opportunities.

smart utility network (SUN): A principally outdoor, low data rate wireless network that supports two-way communications among sensing, measurement, and control devices in the smart grid.

STS seed: A parameter that is part of the seed input to the STS generating DRBG and which may be privileged information or not depending on the application needs.

transaction: The exchange of related, consecutive frames between two peer MAC entities, required for a successful transmission of a MAC Command frame or Data frame.

3.2 Acronyms and abbreviations

Ack	acknowledgment
AEAD	authenticated encryption with associated data
AES	advanced encryption standard
AIFS	acknowledgment interframe spacing
ANPI	average noise power indicator
AOA	angle of arrival
AR	acknowledgment request
ASK	amplitude shift keying
ASN	absolute slot number
ATI	allowed transmission interval
BCH	Bose Chaudhuri Hocquenghem
BDE	bit differential encoding
BLE	battery life extension
BOP	beacon only period
BPM	burst position modulation
BPRF	base pulse repetition frequency
BPSK	binary phase-shift keying
BSN	beacon sequence number
CAP	contention access period
CBC-MAC	cipher block chaining message authentication code
CCA	clear channel assessment
CCM	counter mode encryption and cipher block chaining message authentication code
CCM*	extension of counter mode encryption and cipher block chaining message authentication code
CFP	contention-free period
CID	Company ID

CMB	China medical band
CoU	chirp on ultra wideband
CP	cyclic prefix
CRC	cyclic redundancy check
CS	continuous spectrum
CSK	chirp-shift keying
CSL	coordinated sampled listing
CSM	common signaling mode
CSMA-CA	carrier sense multiple access with collision avoidance
CSS	chirp spread spectrum
DA	device announcement
DAA	detect and avoid
DBS	dedicated beacon slot
DCS	dynamic channel selection
DEMUX	de-multiplexer
DFT	discrete Fourier transform
DPS	dynamic preamble selection
DPSK	differential phase-shift keying
DQCSK	differential quadrature chirp-shift keying
DQPSK	differential quadrature phase-shift keying
DRBG	deterministic random bit generator
DSME	deterministic and synchronous multichannel extension
DSN	data sequence number
DSSS	direct sequence spread spectrum
DS-TWR	double-sided two-way ranging
EBSN	enhanced beacon sequence number
ED	energy detection (also in 10.8.2, extended duration)
EIRP	effective isotropic radiated power
Enh-Ack	enhanced acknowledgment
EPC	enhanced payload capacity
ERDEV	enhanced ranging capable device
ESDU	encapsulated service data unit
EUI-64	64-bit extended unique identifier
EVM	error-vector magnitude
FCS	frame check sequence
FEC	forward error correction
FICS	fragment integrity check sequence
FoM	figure of merit
Frak	fragment acknowledgment
FSK	frequency shift keying
GDB	geolocation database
GFSK	Gaussian frequency-shift keying
GMSK	Gaussian-filtered minimum shift keying
GTS	guaranteed timeslot
HCS	header check sequence
HPRF	higher pulse repetition frequency

HRP	high rate pulse repetition frequency
HRP-ERDEV	high rate pulse repetition frequency UWB PHY based enhanced ranging capable device
ID	identifier
IDFT	inverse discrete Fourier transform
IE	information element
IFS	interframe space or spacing
Imm-Ack	immediate acknowledgment
IPI	idle power indicator
I-RIT	implicit receiver initiated transmission
ISR	interference-to-signal ratio
LBT	listen before talk
LCP	linear combination of pulses
LDPC	low density parity check
LE	low energy
LECIM	low-energy, critical infrastructure monitoring
LEIP	location enhancing information postamble
LFSR	linear feedback shift register
LIFS	long interframe spacing
LMR	land mobile radio
LQI	link quality indication
LRP	low rate pulse repetition frequency
LRP-ERDEV	low rate pulse repetition frequency UWB PHY based enhanced ranging capable device
LR-WPAN	low-rate wireless personal area network
LSB	least significant bit
LTF	long training field
MAC	medium access control
MBAN	medical body area network
MCPS	MAC common part sublayer
MCPS-SAP	MAC common part sublayer service access point
MCS	modulation and coding scheme
MD	multi-superframe duration
MDSSS	multiplexed direct sequence spread spectrum
MFR	MAC footer
MHR	MAC header
MIC	message integrity code
MLME	MAC sublayer management entity
MLME-SAP	MAC sublayer management entity service access point
MPDU	MAC protocol data unit
MPM	multi-PHY management
MSB	most significant bit
MSDU	MAC service data unit
MSK	minimum shift keying
NRNSC	nonrecursive and nonsystematic code
OFDM	orthogonal frequency division multiplexing
OOK	on-off keying
O-QPSK	offset quadrature phase-shift keying

OUI	organizationally unique identifier
OVSF	orthogonal variable spreading factor
OWR	one-way ranging
PAN	personal area network
PBFSK	pulsed binary frequency shift keying
PCA	priority channel access
PD-SAP	physical layer data service access point
PER	packet error rate
P-FSK	position-based frequency shift keying
PHR	PHY header
PHY	physical layer
PIB	personal area network information base
PICS	protocol implementation conformance statement
PLME	physical layer management entity
PLME-SAP	physical layer management entity service access point
PN	pseudo-random noise
PPDU	PHY protocol data unit
PPM	pulse position modulation
PRBS	pseudo-random binary sequence
PRF	pulse repetition frequency
PRP	pulse repetition period
PSD	power spectral density
PSDU	PHY service data unit
PSR	preamble symbol repetitions
QAM	quadrature amplitude modulation
QPSK	quadrature phase-shift keying
RBS	ranging beacon slot
RCC	rail communications and control
RCCN	rail communications and control network
RCM	ranging control message
RCPI	received channel power indicator
RDEV	ranging-capable device
RF	radio frequency
RFID	radio frequency identification
RFRAME	ranging frame
RIT	receiver initiated transmission
RMARKER	ranging marker
RSC	recursive and systematic code
RS-GFSK	rate switch Gaussian frequency shift keying
RSNI	received signal noise indicator
RSSI	receive signal strength indicator
RSTU	ranging scheduling time unit
RX	receive or receiver
SAB	slot allocation bitmap
SD	superframe duration
SF	spreading factor

SFD	start-of-frame delimiter
SHR	synchronization header
SIFS	short interframe spacing
SiPC	single parity check
SNR	signal-to-noise ratio
SP3	scrambled timestamp sequence packet configuration option three
SPC	super PAN coordinator
SRBD	start of radio-burst delimiter
SRM	spectrum resource measurement
SRMARKER	STS RMARKER
SS-TWR	single-sided two-way ranging
STF	short training field
STS	scrambled timestamp sequence
SUN	smart utility network
TASK	ternary amplitude shift keying
TBPC	turbo product code
TDOA	time difference of arrival
TID	transaction identifier
TMCTP	TVWS multichannel cluster tree PAN
TOF	time of flight
TPC	transmission power control
TRLE	timeslot relaying based link extension
TSCH	timeslotted channel hopping
TVWS	television white space
TWR	two-way ranging
TX	transmit or transmitter
UWB	ultra wideband
WPAN	wireless personal area network

4. Format conventions

4.1 General

Throughout this standard, unless otherwise stated, data structures exposed in interfaces are represented using the conventions and formats defined in this clause.

NOTE—It is important to note that interfaces are depicted in this standard as bit serial by convention but can be implemented in other forms, e.g., 4- or 8-bit parallel.¹⁷

Within the PHY, data structures are passed to the reference modulator input in bit-serial convention. PHY specific coding may change the bit-order and encode multiple information bits into symbols. Hence the over-the-air interface may express the data structure content in a manner different than the conventions defined here.

After all applicable expansion, the size of a MAC frame shall be less than the maximum PHY service data unit (PSDU) size supported by the PHY in use.

4.2 Fields

The general format of a data structure is shown in Figure 4-1. Each field is represented by a column in the figure giving the size of the field and the name and/or type of the datum encoded in the field. The convention of a data structure is recursive in that a field may contain a data structure that is, in turn, composed of fields.

Octets: 2	Bits: 0–5	6–7	...
Field Name/Type (Number datum)	Field Name/Type (Bit string datum)	Field Name/Type (Bit string datum)	...

Figure 4-1—General data structure format

The form <Octets: n > means the field is n octets long. The form <Bits: n > or <Bits: $m-n$ > means bit number n or bits m to n of the data structure. In a figure, if a field length appears without either Octets or Bits, then the preceding units apply.

The form <Octets: $n/m/l$ > means the field can be n , m , or l octets long.

Fields are concatenated into larger data structures, e.g., Figure 4-1 represents a data structure with 3 fields of length 2 octets, 6 bits, and 2 bits for a total size of 3 octets.

Order of representation is strict with the leftmost field as shown in any figure occurring before the next field to its right. The second field from the left occurs before the third field and so on.

Significance, as expressed in the terms least significant bit (LSB) and most significant bit (MSB), only applies to numbers as defined in 4.3. All other fields are treated as strings.

The convention of “processing a data structure” or “transmitting a data structure” mean treatment of the content of the data structure in the order defined in the following subclauses.

¹⁷ Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

4.3 Numbers

Numbers are represented in decimal (nnn), binary (0bnnn), or hexadecimal (0xnnn) notation with the number of digits indicated. For example, 0b001 is a 3-digit binary number of value 1 and 0x001 is a 3-digit hexadecimal number of value 1. Numbers encoded in fields are either signed or unsigned integers unless explicitly defined otherwise. Other formats (e.g., a field containing a floating point number) are stated in the field definition where applicable.

When represented in fields, numbers are expressed with LSB leftmost and MSB rightmost as shown in Figure 4-2 for an n -bit unsigned integer. Note that this is the inverse of the number representations 0bnnn and 0xnnn and of common number representations used in mathematical notations. For example, the number 0x47 would be represented in an 8-bit field as 1110 0010.

Bit:0	...	7	Bits 8–(n – 2)	$n – 1$
LSB	...	—	Subsequent octets	MSB

Figure 4-2—General number field format

Numbers of size greater than 1 octet occur with the octet containing the least significant bits first (leftmost) followed by octets containing bits of increasing significance to the right.

Unless stated otherwise in the definition of a field, a number in a field shall be formatted as an unsigned integer.

4.4 Strings

A string of length k bits is represented as a bit sequence numbered from 0 to $k – 1$. Bit 0 occurs first and is represented as the leftmost bit of a string field. Bit 1 occurs to the right of bit 0 and so on until bit ($k – 1$). This is illustrated in Figure 4-3.

Bits:0	...	7	Bits 8–(k – 1)
String bit 0	...	String bit 7	String bits 8 to $k – 1$

Figure 4-3—General string field format

A string of length greater than 1 octet is represented by the octet containing the lowest numbered bits first and leftmost, followed by octets containing increasing bit numbers to the right.

4.5 Transmission order

4.5.1 Address field

For every address field, the bit transmission order shall be performed from the right most octet (RMO) to the left most octet (LMO) in the field, and inside an octet from the LSB to the MSB.

Figure 4-4 shows the MAC Address field containing a 64-bit MAC address. For this example the MAC address value is assumed to be AC-DE-48-23-45-67-89-01.¹⁸

¹⁸ This example octet string is based on an OUI value that could be in use and is not reserved.

Octets: 8
MAC Address

Figure 4-4—Field containing a 64-bit MAC address

Figure 4-5 shows the bit transmission order of the MAC Address field of Figure 4-4.

RMO → LMO	Octet 8 RMO	Octet 7	Octet 6	Octet 5	Octet 4	Octet 3	Octet 2	Octet 1 LMO
	01	89	67	45	23	48	DE	AC
LSB → MSB	10000000	10010001	11100110	10100010	11000100	00010010	01111011	00110101

Transmission order →

Figure 4-5—Transmission order for the MAC Address field

4.5.2 Vendor OUI/CID transmission order

Vendor organizationally unique identifier (OUI) bit transmission order shall be performed from the right most octet (RMO) to the left most octet (LMO) in the field, and inside an octet from the LSB to the MSB.

Figure 4-6 shows the Vendor OUI/CID field. For this example, the Vendor OUI/CID field value is assumed to be AC-DE-48.

Octets: 3
Vendor OUI/CID

Figure 4-6—Vendor OUI/CID field

Figure 4-7 shows the bit transmission order of the Vendor OUI/CID field of Figure 4-6.

RMO → LMO	Octet 3 RMO	Octet 2	Octet 1 LMO
	48	DE	AC
LSB → MSB	00010010	01111011	00110101

Figure 4-7—Transmission order for the Vendor OUI/CID field

4.6 Reserved fields and values

Each bit within any Reserved field shall be set to zero on transmission and shall be ignored on reception.

A decision should never be made based on the contents of any Reserved field or field containing a reserved value.

5. General description

5.1 Introduction

A low-rate wireless personal area network (LR-WPAN) is a simple, low-cost communication network that allows wireless connectivity in applications with limited power and relaxed throughput requirements. The main objectives of an LR-WPAN are ease of installation, reliable data transfer, extremely low cost, and a reasonable battery life, while maintaining a simple and flexible protocol.

This standard defines one MAC and multiple PHYs operating in a variety of frequency bands, as described in 11.1.

Supplemental information for various industrial domains is described in “Applications of IEEE Std 802.15.4” [B4].¹⁹

5.2 Special application spaces

5.2.1 General

Although this standard is intended to address many diverse application spaces, some application spaces have unique requirements, which called for specific elements to be added to this standard. These application spaces are as follows:

- Smart utility network (SUN) as described in 10.14.
- Rail communications and control (RCC) as described in 10.13.
- Television white space (TVWS) as described in 10.7.
- Low-energy, critical infrastructure monitoring (LECIM) as described in 10.15.
- Radio frequency identification (RFID) as described 5.2.2.
- Medical body area network (MBAN) services as described in 5.2.3.
- China medical band (CMB) as described in 5.2.4.

5.2.2 Radio frequency identification (RFID)

Active RFID devices are used to identify and often locate people or objects in industrial or commercial environments. Typical applications include asset management, inventory management, process control and automation, safety, and accountability.

In its simplest form an active RFID system comprises a number of transmit-only tags that periodically transmit a packet containing a unique identifier (ID) and a small amount of data. The packet is received by one or more readers that may simply register the tag as present, may employ further processing to determine the location of the tag, or forward data to an application server. More complex active RFID systems might employ two-way communications with the tag for control, communication, and coordination.

5.2.3 Medical body area network (MBAN) services

Some countries have allocated spectrum for MBAN services on a secondary basis such that MBAN devices are required to protect all primary users and accept possible interference from those users. MBAN devices operating within this allocated spectrum conform to a set of rules that restrict use of the band to only medical, non-voice use under direction of a healthcare practitioner, among other requirements. When a

¹⁹ The numbers in brackets correspond to the numbers of the bibliography in Annex A.

primary user is making use of a portion of the band, MBAN devices vacate that portion of the band. Use of the band by the primary user is, in general, scheduled well in advance, allowing MBAN users to share the band in an orderly manner.

5.2.4 China medical band (CMB)

The Ministry of Industry and Information Technology (MIIT) of the People's Republic of China has approved the 174–216 MHz, 407–425 MHz, and 608–630 MHz bands for medical information transmission.

CMB devices operating within these bands conform to a set of rules specified in MIIT Doc 423-2005 [B34], which restricts use of the band to only medical, non-voice use under direction of a healthcare practitioner, among other requirements.

This standard defines a PHY for devices operating on Chinese-approved bands for medical signals.

5.3 Components of the IEEE 802.15.4 WPAN

A system conforming to this standard consists of several components. The most basic is the device. A device has a single radio interface that implements an IEEE 802.15.4 MAC and PHY. Two or more devices communicating on the same physical channel constitute a wireless personal area network (WPAN).

5.4 Network topologies

5.4.1 General

Depending on the application requirements, an IEEE 802.15.4 LR-WPAN operates in either of two topologies: the star topology or the peer-to-peer topology. Both are shown in Figure 5-1. In the star topology, the communication is established between devices and a single central controller, called the personal area network (PAN) coordinator. A device typically has some associated application and is either the initiation point or the termination point for network communications. The PAN coordinator is the primary controller of the PAN. All devices operating on a network of either topology have unique addresses, referred to as extended addresses. In addition, a device can be assigned a short address during the association process. A device will use either the extended address or the short address for communication within the PAN. The PAN coordinator will often be mains powered, while the devices will likely be battery powered. Applications that benefit from a star topology include home automation, personal computer peripherals, games, and personal health care.

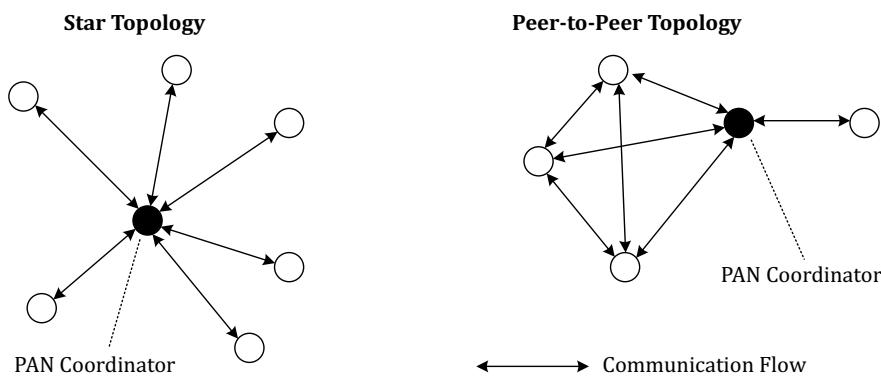


Figure 5-1—Star and peer-to-peer topology examples

The peer-to-peer topology also has a PAN coordinator; however, it differs from the star topology in that any device is able to communicate with any other device as long as they are in range of one another. Peer-to-peer topology allows more complex network formations to be implemented, such as mesh networking topology. Applications such as industrial control and monitoring, wireless sensor networks, asset and inventory tracking, intelligent agriculture, and security would benefit from such a network topology. A peer-to-peer network allows multiple hops to route messages from any device to any other device on the network. Such functions can be added at the higher layer, and they are not part of this standard.

Each independent PAN selects a unique ID. This PAN ID allows communication between devices within a network using short addresses and enables transmissions between devices across independent networks. The mechanism by which identifiers are chosen is outside the scope of this standard.

The network formation is performed by the higher layer, which is not part of this standard.

5.4.2 Star network formation

The basic structure of a star network is illustrated in Figure 5-1. After a device is activated, it can establish its own network and become the PAN coordinator. All star networks operate independently from all other star networks currently in operation. This is achieved by choosing a PAN ID that is not currently used by any other network within the radio communications range. Once the PAN ID is chosen, the PAN coordinator allows other devices to join its network. The higher layer can use the procedures described in 6.4 to form a star network.

5.4.3 Peer-to-peer network formation

In a peer-to-peer topology, each device is capable of communicating with any other device within its radio communications range. One device is nominated as the PAN coordinator, for instance by virtue of being the first device to communicate on the channel. Further network structures are constructed out of the peer-to-peer topology, and it is possible to impose topological restrictions on the formation of the network.

An example of the use of the peer-to-peer communications topology is the cluster tree. The cluster tree network is a special case of a peer-to-peer network. Intermediate devices provide synchronization services to other devices. Only one device in the network is the overall PAN coordinator, potentially because it has greater computational resources than any other device in the PAN. The PAN coordinator forms the first cluster by choosing an unused PAN ID and broadcasting beacon frames to neighboring devices. A contention resolution mechanism is required if two or more devices simultaneously attempt to establish themselves as PAN coordinators; however, such a mechanism is outside the scope of this standard. A candidate device receiving a beacon frame is able to request to join the network at the PAN coordinator. If the PAN coordinator permits the device to join, it adds the new device as a child device in its neighbor list. Then the newly joined device adds the PAN coordinator as its parent in its neighbor list and begins transmitting periodic beacons; other candidate devices are able to then join the network at that device. If the original candidate device is not able to join the network at the PAN coordinator, it will search for another parent device. The detailed procedures describing how a PAN is started and how devices join a PAN are found in 6.4 and 10.21.

5.5 Architecture

5.5.1 General

The IEEE 802.15.4 architecture is defined in terms of a number of blocks in order to simplify the standard. These blocks are called layers. Each layer is responsible for one part of the standard and offers services to the higher layers.

The interfaces between the layers serve to define the logical links that are described in this standard.

An LR-WPAN device contains at least one PHY, which contains the radio frequency (RF) transceiver along with its low-level control mechanism, and a MAC sublayer that provides access to the physical channel for all types of transfer. Figure 5-2 shows these blocks in a graphical representation.

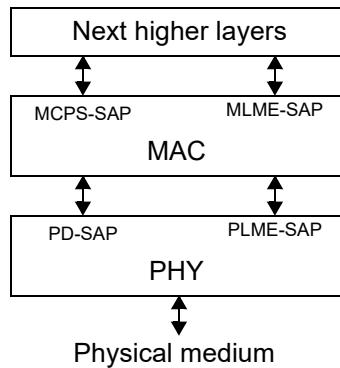


Figure 5-2—LR-WPAN device architecture

The next higher layers, shown in Figure 5-2, consist of a network layer, which provides network configuration, manipulation, and message routing, and an application layer, which provides the intended function of the device. The definition of these layers is outside the scope of this standard.

5.5.2 PHY

The features of the PHY are activation and deactivation of the radio transceiver, energy detection (ED), link quality indication (LQI), channel selection, clear channel assessment (CCA), ranging and transmitting as well as receiving packets across the physical medium. The high rate pulse repetition frequency (HRP) ultra wideband (UWB) PHY also has the feature of precision ranging.

Coexistence with other wireless standards has been analyzed for the PHYs defined in this standard. These analyses can be found in the following documents:

- For the offset quadrature phase-shift keying (O-QPSK) PHY, binary phase-shift keying (BPSK) PHY, CSSS PHY, HRP UWB PHY, and Gaussian frequency-shift keying (GFSK) PHY: “Coexistence analysis of IEEE Std 802.15.4 with other IEEE standards and proposed standards” [B8].
- For the minimum shift keying (MSK) PHY, with the exception of the 2000 kb/s data rate, and the low rate pulse repetition frequency (LRP) UWB PHY: “TG4f Coexistence Assurance Document” [B32].
- For the MSK PHY using the 2000 kb/s data rate: “TG4t Coexistence Assurance Document” [B28].
- For the TVWS frequency shift keying (FSK) PHY, TVWS orthogonal frequency division multiplexing (OFDM) PHY, and TVWS-NB-OFDM PHY: Chang and Seibert [B7].
- For the ternary amplitude shift keying (TASK) PHY and rate switch Gaussian frequency shift keying (RS-GFSK) PHY: Nair, et al. [B25].
- For UWB “Coexistence Document for IEEE 802.15.4z” [B9].
- For the split mode LECIM FSK PHY: “TG4w Coexistence Document” [B33].
- For supporting higher data rates in the 920 MHz band using GFSK modulation: “IEEE 802.15.4aa Coexistence Assessment Document” [B12].

5.5.3 MAC sublayer

The MAC sublayer provides two services: the MAC data service and the MAC management service interfacing to the MAC sublayer management entity (MLME) service access point (SAP) (known as MLME-SAP). The MAC data service enables the transmission and reception of MAC protocol data units (MPDUs) across the PHY data service.

The features of the MAC sublayer are beacon management, channel access, guaranteed timeslot (GTS) management, frame validation, acknowledged frame delivery, association, and disassociation. In addition, the MAC sublayer provides hooks for implementing application-appropriate security mechanisms.

5.6 Functional overview

5.6.1 Scheduled access

There are multiple superframe structures defined in this standard as follows:

- Beacon superframe as described in 10.2.
- Deterministic and synchronous multichannel extension (DSME) superframe as described in 10.4.
- Timeslotted channel hopping (TSCH) slotframes as described in 10.3.
- TVWS multichannel cluster tree PAN (TMCTP) superframe as described in 10.8.

5.6.2 Data transfer model

5.6.2.1 Types of data transfer models

The data transfer models used in this standard are as follows:

- Transfer to a coordinator in which a device transmits the data
- Indirect transfer from a coordinator in which the device receives the data
- Transfer between two peer devices

If a frame that is correctly received requests an acknowledgment, the device that received the frame will respond with one of the acknowledgment (Ack) frames: immediate acknowledgment (Imm-Ack), enhanced acknowledgment (Enh-Ack), or fragment acknowledgment (Frak), depending on the state of the network and the version number of the frame that was received.

5.6.2.2 Data transfer to a coordinator

When a device wishes to transfer data to a coordinator in a PAN using periodic beacons for synchronization, it first listens for the beacon. When the beacon is found, the device synchronizes to the PAN. At the appropriate time, the device transmits its Data frame to the coordinator.

When a device wishes to transfer data in a PAN not using periodic beacons for synchronization, it just transmits its Data frame to the coordinator.

5.6.2.3 Indirect data transfer from a coordinator

When the coordinator wishes to transfer data to a device in a PAN using superframe structure, it indicates in the beacon, as defined in 7.3.1.6, that the data message is pending. The device periodically listens to the beacon and, if a message is pending, transmits a Data Request command. The pending Data frame is then sent by the coordinator. Upon successful completion of the data transaction, the message is removed from the list of pending messages in the beacon.

When a coordinator wishes to transfer data to a device in a PAN not using superframe structure, it stores the data for the appropriate device to make contact and request the data. A device requests data by transmitting a Data Request command to its coordinator. If a Data frame is pending, the coordinator transmits the Data frame. If a Data frame is not pending, the coordinator indicates this fact either in the Ack frame following the Data Request command, if an acknowledgment was requested, or in a Data frame with a zero-length payload, as defined in 10.22.

5.6.2.4 Peer-to-peer data transfers

For peer-to-peer transfers, a target device will either receive constantly or synchronize with the originator device. In the former case, the originator device attempts to transmit the data when it gains access to the channel. In the latter case, other measures need to be taken in order to achieve synchronization.

5.6.3 Frame structure

The frame structures have been designed to keep the complexity to a minimum while at the same time making them sufficiently robust for transmission on a noisy channel.

The MAC frames are passed to the PHY as the PSDU, which becomes the PHY payload. The typical structure of a PHY protocol data unit (PPDU) is illustrated in Figure 5-3.

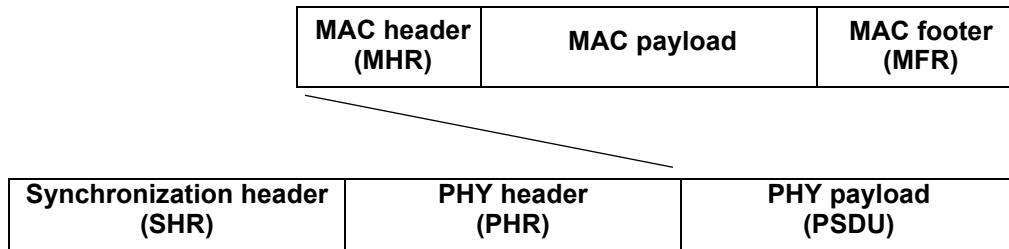


Figure 5-3—Schematic view of the PPDU

The format of the synchronization header (SHR), PHY header (PHR), PPSU, and any other PHY specific fields is defined for each of the PHYs in their respective clause.

The MAC header (MHR) and MAC footer (MFR) are defined in 7.2.

5.6.4 Information element (IEs)

This standard makes use of IEs to transfer formatted data between layers and between devices. IEs consist of an identification, a length, and the information element (IE) content. Devices can accept or discard a particular element if the identification is known, and skip over unknown IEs.

5.6.5 Access methods

5.6.5.1 Overview

The access methods defined in this standard are as follows:

- Unslotted carrier sense multiple access with collision avoidance (CSMA-CA) used in PANs not using superframe structure, as described in 6.3.2.1
- Slotted CSMA-CA used in PANs using superframe structure, as described in 10.11
- TSCH CCA used in non-shared slots in a TSCH PAN, as described in 10.3.2.1
- TSCH CSMA-CA used for shared slots in a TSCH PAN, as described in 10.3.2.2
- CSMA-CA with priority channel access (PCA) for critical events, as described in 10.10.2.1
- LECIM ALOHA with PCA, as defined in 10.10.2.2

5.6.5.2 Frame acknowledgment

A successful reception and validation of a frame is optionally confirmed with an acknowledgment, as described in 6.6.3.

The receiving device can insert additional content in an Enh-Ack frame encapsulated as IEs. If the originator does not understand the IE content of the Enh-Ack frame, it is ignored, but the transmission is considered successful.

If the originator does not receive an acknowledgment after some period, it assumes that the transmission was unsuccessful and retries the frame transmission. If an acknowledgment is still not received after several retries, the originator can choose either to terminate the transaction or to try again. When the acknowledgment is not required, the originator assumes the transmission was successful.

5.6.5.3 Frak

The Frak is used during the fragment sequence transfer to determine which fragments have been received successfully and which fragments need to be retransmitted. A Frak includes the status of one or more fragments. The format of the Frak is given in 23.3.7.3.

5.6.5.4 Data verification

A cyclic redundancy check (CRC) is used to detect errors in an MSDU, as defined in 7.2.11.

To accommodate individual fragment acknowledgments, a fragment integrity check sequence (FICS) is included with each fragment. The recipient uses the FICS and fragment number to determine which fragments of the sequence have been received correctly and which are missing. The FICS is described in 23.3.4.

5.6.6 Power consumption considerations

5.6.6.1 General

In many applications that use this standard, devices will be battery powered, and battery replacement or recharging in relatively short intervals is impractical. Therefore, the power consumption is of significant concern. This standard was developed for devices with limited power supply availability in mind. However, the physical implementation of this standard may require additional power management considerations that are beyond the scope of this standard.

The protocol has been developed to favor battery-powered devices. However, in certain applications, some of these devices could potentially be mains powered. Battery-powered devices will require duty-cycling to reduce power consumption. These devices will spend most of their operational life in a sleep state; however, each device periodically listens to the RF channel in order to determine whether a message is pending. This mechanism allows the application designer to decide on the balance between battery consumption and message latency. Continuously powered devices have the option of listening to the RF channel continuously.

In addition to the power-saving features of the LR-WPAN system, the HRP UWB PHY also provides a hybrid modulation that enables very simple, noncoherent receiver architectures to further reduce power consumption and implementation complexity.

5.6.6.2 Low-energy mechanisms

Low-energy mechanisms, coordinated sampled listening (CSL), as defined in 10.5.4, and receiver initiated transmission (RIT), as described in 10.6, are provided to further reduce energy consumption by allowing devices to communicate while maintaining low duty cycles.

5.6.7 Security

From a security perspective, wireless ad hoc networks are no different from any other wireless network. They are vulnerable to passive eavesdropping attacks and active tampering because physical access to the wire is not required to participate in communications. The very nature of ad hoc networks and their cost objectives impose additional security constraints, which perhaps make these networks the most difficult environments to secure. Devices are low-cost and have limited capabilities in terms of computing power, available storage, and power drain; and it cannot always be assumed they have a trusted computing base nor a high-quality random number generator aboard. Communications cannot rely on the online availability of a fixed infrastructure and might involve short-term relationships between devices that never have communicated before. These constraints severely limit the choice of cryptographic algorithms and protocols and influence the design of the security architecture because the establishment and maintenance of trust relationships between devices need to be addressed with care. Most of these security architectural elements can be implemented at higher layers and, therefore, are outside the scope of this standard. IEEE Std 802.15.9 can be used to create keys for the security layer.

The cryptographic mechanism in this standard is based on symmetric-key cryptography and uses keys that are provided by higher layer processes. The establishment and maintenance of these keys are outside the scope of this standard. The mechanism assumes a secure implementation of cryptographic operations and secure and authentic storage of keying material.

The cryptographic mechanism provides particular combinations of the following security services:

- *Data confidentiality*: Assurance that transmitted information is disclosed only to parties for whom it is intended.
- *Data authenticity*: Assurance of the source of transmitted information (and, hereby, that information was not modified in transit).
- *Replay protection*: Assurance that duplicate information is detected.

The actual frame protection provided can be adapted on a frame-by-frame basis and allows for varying levels of data authenticity (to minimize security overhead in transmitted frames where required) and for optional data confidentiality.

Cryptographic frame protection uses either a key shared between two peer devices (link key) or a key shared among a group of devices (group key), thus allowing some flexibility and application-specific tradeoffs between key storage and key maintenance costs versus the cryptographic protection provided. If a group key

is used for peer-to-peer communication, protection is provided only against outsider devices and not against potential malicious devices in the key-sharing group.

For more detailed information on the cryptographic security mechanisms used for protected MAC frames following this standard, refer to Clause 9.

5.6.8 Enabling spectrum resource measurement capability

Spectrum resource measurement (SRM) enables devices to gather a variety of data for evaluating radio link performance, which contributes to the selection of the best available PAN for joining and efficient radio spectrum usage for the selected PAN. As shown in Figure 5-4, the device obtains radio link characteristics by local measurements or via exchange of information with other devices via reporting messages all the way to the PAN coordinator. The PAN coordinator is also able to disseminate information to the devices in the PAN, such as the maximum transmit power, by which the receiving devices can set their radio parameters in a unified manner. SRM data is also made available to the upper protocol layers, which is able to use it for controlling the lower layer or their applications.

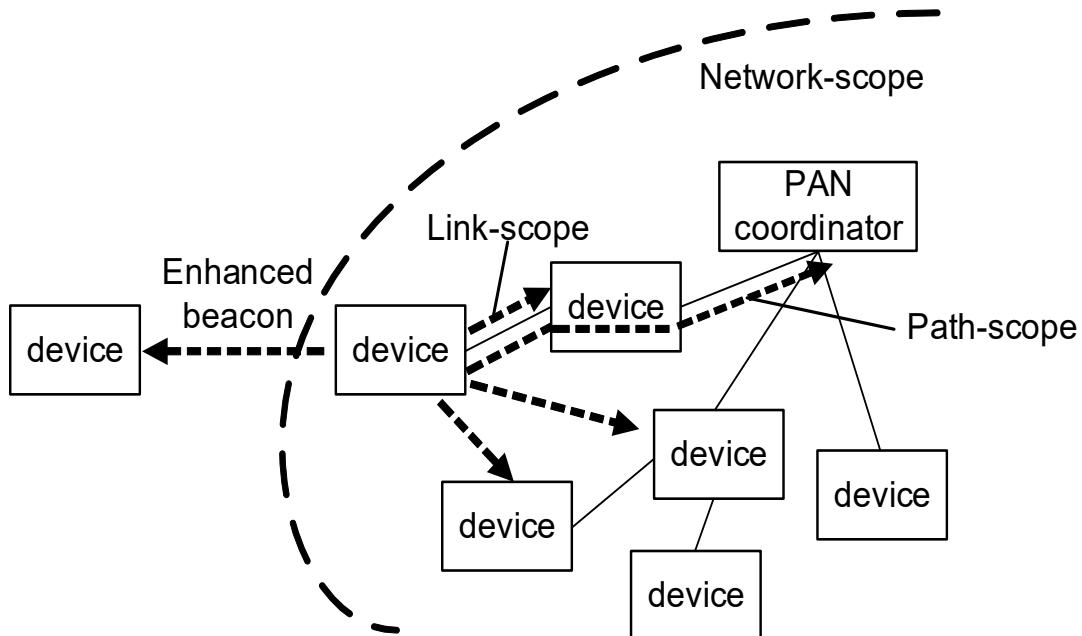


Figure 5-4—Scope-based forwarding control

The measurement of SRM metrics is conducted only when the device is capable of doing it. In the case of low energy (LE) transmission and reception, for example, even if the requesting device requests the peer device to measure SRM metrics for a specific duration of time, the requested device can do it only when the receiver is enabled.

In the case of TSCH, there are three modes of measurement operation:

- *Full measurement*: The device conducts the measurement for a specified duration of time following the channel sequence as necessary.
- *Channel-specific measurement*: The device conducts the measurement only when it is on the specified channel within the hopping sequence. The device puts the measured data together and

calculates the performance metrics. The obtained result is the characteristics of the specified channel.

- *Link-specific measurement:* The device conducts the measurement only when it is on a specific link, which is represented by *macLinkHandle* defined in Table 10-18. The device puts the measured data together and calculates the performance metrics. The obtained result is the characteristics of the specified link.

5.7 Concept of primitives

The services of a layer are the capabilities it offers to the user in the next higher layer or sublayer by building its functions on the services of the next lower layer. This concept is illustrated in Figure 5-5, showing the service hierarchy and the relationship of the two correspondent users and their associated layer (or sublayer) peer protocol entities.

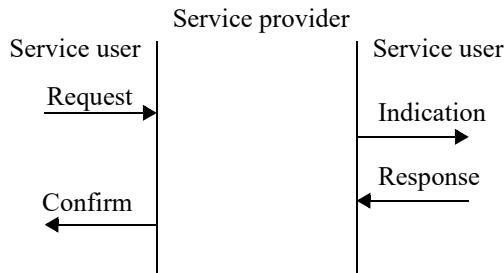


Figure 5-5—Service primitives

The services are specified by describing the information flow between the N-user and the N-layer. This information flow is modeled by discrete, instantaneous events, which characterize the provision of a service. Each event consists of passing a service primitive from one layer to the other through a layer SAP associated with an N-user. Service primitives convey the required information by providing a particular service. These service primitives are an abstraction because they specify only the provided service rather than the means by which it is provided. This definition is independent of any other interface implementation.

A service is specified by describing the service primitives and parameters that characterize it.

A primitive can be one of four generic types:

- *Request:* The request primitive is used to request that a service be initiated.
- *Indication:* The indication primitive is used to indicate to the user an internal event.
- *Response:* The response primitive is used to complete a procedure previously invoked by an indication primitive.
- *Confirm:* The confirm primitive is used to convey the results of one or more associated previous service requests.

6. MAC functional description

6.1 Optional features

All features described in this clause are mandatory, and all optional features are moved to Clause 10.

6.2 Device types and conventions

Constants and PAN information base (PIB) attributes that are specified and maintained by the MAC sublayer or PHY layer are written in the text in italics. Constants have a general prefix of “a”, for example *aBaseSlotDuration*, and the MAC constants are listed in Table 8-36, while the PHY constants are listed in Table 12-1. MAC PIB attributes have a general prefix of “mac”, for example *macExtendedAddress*, and are listed in Table 8-36, while the security attributes are listed in Table 9-8. PHY PIB attributes have a general prefix of “phy”, for example *phyCurrentChannelInfo*, and are listed in tables 12-3.

Some of the timing parameters in definition of the MAC are in units of PHY symbols. For PHYs that have multiple symbol periods, the duration to be used for the MAC parameters is defined in that PHY clause.

The broadcast short address is defined to be 0xffff. The broadcast PAN ID is defined to be 0xffff. The term broadcast address refers to either a broadcast short address or the 64-bit broadcast MAC address that is defined in IEEE Std 802 to be 0xffff ffff ffff ffff.

Acknowledgment frames and timers are not shown in the message sequence charts unless they affect the behavior of that procedure.

6.3 Channel access

6.3.1 Interframe space (IFS)

The MAC sublayer needs a finite amount of time to process data received by the PHY. To allow for this, two successive frames transmitted from a device shall be separated by at least an interframe space (IFS) period; if the first transmission requires an acknowledgment, the separation between the Ack frame and the second transmission shall be at least the acknowledgment interframe spacing (AIFS). The length of the IFS period is dependent on the size of the frame that has just been transmitted. Frames (i.e., MPDUs) of up to *aMaxSifsFrameSize* shall be followed by a short interframe space (SIFS) period of a duration of at least $\max(\text{macSifsPeriod}, \text{aTurnaroundTime})$. Frames (i.e., MPDUs) with lengths greater than *aMaxSifsFrameSize* shall be followed by the maximum of long interframe spacing (LIFS) of a duration of at least $\max(\text{macLifsPeriod}, \text{aTurnaroundTime})$. These concepts are illustrated in Figure 6-1.

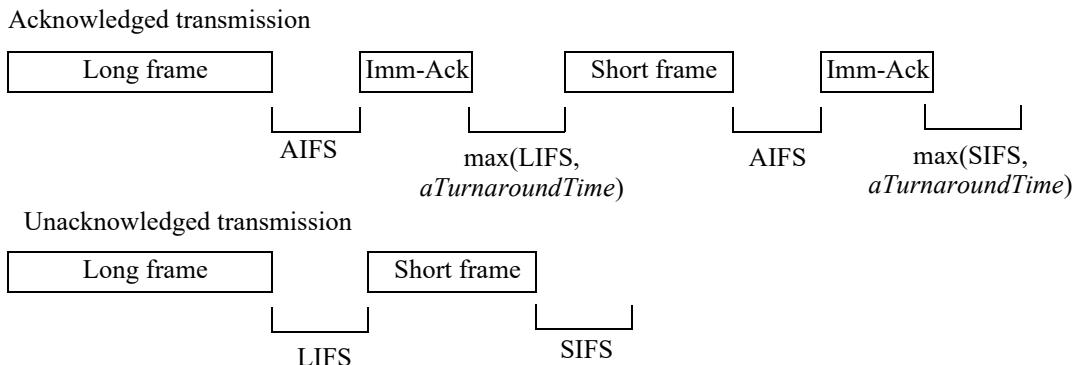


Figure 6-1—IFS usage

In order to provide sufficient time for the PHY to transition from transmit (TX) to receive (RX) or RX to TX, the following relation holds:

$$\text{AIFS} \leq \text{SIFS} < \text{LIFS}$$

The CSMA-CA algorithm shall take this requirement into account for transmissions in the contention access period (CAP). The timing of the transmission of an Ack frame, AIFS, is defined in 6.6.3.3.

6.3.2 Random access methods

6.3.2.1 CSMA-CA algorithm

The CSMA-CA algorithm shall be used before the transmission of data or MAC commands transmitted within the CAP, unless the frame can be quickly transmitted following the acknowledgment of a Data Request command, as defined in 10.22.4.1.

In a PAN using superframe structure the MAC sublayer shall employ the slotted version of the CSMA-CA algorithm for transmissions in the CAP of the superframe described in 10.11. Conversely, if periodic beacons are not being used in the PAN or if a beacon could not be located in a PAN using periodic beacons, the MAC sublayer shall transmit using the unslotted version of the CSMA-CA algorithm described here. In both cases, the algorithm is implemented using units of time called backoff periods, where one backoff period shall be equal to *macUnitBackoffPeriod*.

Each device shall maintain two variables for each transmission attempt: *NB*, and *BE*. *NB* is the number of times the CSMA-CA algorithm was required to back off while attempting the current transmission; this value shall be initialized to zero before each new transmission attempt. *BE* is the backoff exponent, which is related to how many backoff periods a device shall wait before attempting to assess a channel. *BE* shall be initialized to the value of *macMinBe*.

NOTE—If *macMinBe* is set to zero, collision avoidance will be disabled during the first iteration of this algorithm.

Although the receiver of the device is enabled during the CCA analysis portion of this algorithm, the device may discard any frames received during this time.

Figure 6-2 illustrates the steps of the CSMA-CA algorithm. If the algorithm ends in “Success”, the MAC is allowed to begin transmission of the frame. Otherwise, the algorithm terminates with a channel access failure.

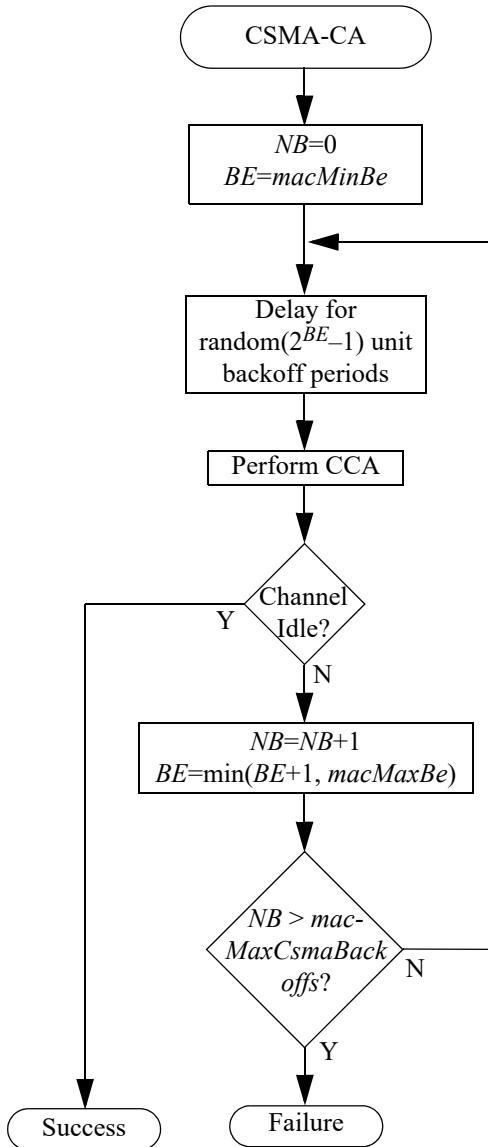


Figure 6-2—CSMA-CA algorithm

6.4 Starting and maintaining PANs

6.4.1 Scanning through channels

6.4.1.1 General

All devices shall be capable of performing passive scan across a specified set of channels. In addition, devices may be able to perform ED, orphan, active, and enhanced active scans.

A device is instructed to begin a channel scan through the MLME-SCAN.request primitive, as described in 8.2.8.2. Channels are scanned in order from the lowest channel number to the highest. For the duration of the scan, the device shall suspend beacon transmissions, if applicable, and shall only accept frames received over the PHY data service that are relevant to the scan being performed. For HRP UWB and chirp spread

spectrum (CSS) PHYs, each preamble code appropriate to the specified channel is scanned. Upon the conclusion of the scan, the coordinator device in a PAN using periodic beacons shall recommence beacon transmissions. The results of the scan shall be returned via the MLME-SCAN.confirm primitive as described in 8.2.8.3.

6.4.1.2 Passive channel scan

A passive channel scan allows a device to locate any coordinator transmitting Beacon frames within its radio communications range. A message sequence chart for a passive scan is illustrated in Figure 6-3.

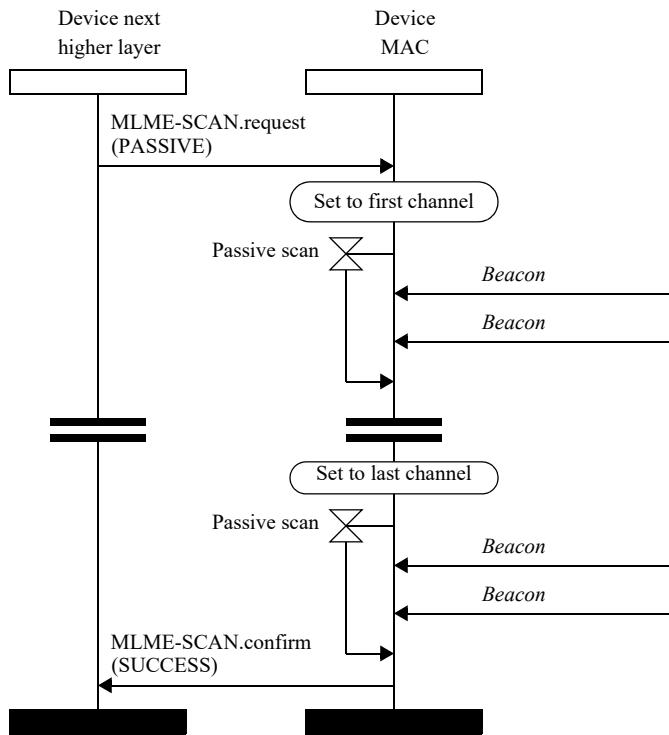


Figure 6-3—Passive scan message sequence chart

During a scan, the MAC sublayer shall discard all frames received over the PHY data service that are not Beacon frames. If a Beacon frame is received that contains the address of the scanning device in its set of pending addresses, the scanning device shall not attempt to extract the pending data.

A passive scan over a specified set of channels is requested using the MLME-SCAN.request primitive with the ScanType parameter set to indicate passive scan. For each channel, the device shall first switch to the channel, by setting *phyCurrentChannelInfo* accordingly.

After switching to the channel, the device shall enable its receiver for at most the period set by the ScanDuration parameter of the MLME-SCAN.request primitive. During this time, the device shall reject all frames that are not Beacon frames and record the information contained in all unique beacons in a PAN descriptor structure, as described in Table 8-3, including the channel information and, if required, the preamble code.

If a Beacon frame is received when *macAutoRequest* is set to TRUE, the list of PAN descriptor structures shall be stored by the MAC sublayer until the scan is complete; at this time, the list shall be sent to the next higher layer in the PanDescriptorList parameter of the MLME-SCAN.confirm primitive. A device shall be

able to store at least one PAN descriptor. A Beacon frame shall be assumed to be unique if it contains both a PAN ID and a source address that have not been seen before during the scan of the current channel.

If a Beacon frame is received when *macAutoRequest* is set to FALSE, each recorded PAN descriptor is sent to the next higher layer in a separate MLME-BEACON-NOTIFY.indication primitive as described in 8.2.4.3. A received Beacon frame containing a nonzero-length payload shall also cause the PAN descriptor to be sent to the next higher layer via the MLME-BEACON-NOTIFY.indication primitive. Once the scan with *macAutoRequest* set to FALSE is complete, the MLME-SCAN.confirm primitive shall be issued to the next higher layer with a null PanDescriptorList.

If a protected Beacon frame is received, i.e., the Security Enabled field is set to one, the device shall attempt to unsecure the Beacon frame using the unsecuring process described in 9.2.4.

The security-related elements of the PAN descriptor corresponding to the beacon, as defined in Table 8-3, shall be set to the corresponding parameters returned by the unsecuring process. The SecurityStatus element of the PAN descriptor shall be set to SUCCESS if the Status from the unsecuring process is SUCCESS and set to one of the other Status codes indicating an error in the security processing otherwise.

The information from the frame to be unsecured shall be recorded in the PAN descriptor even if the Status from the unsecuring process indicated an error.

If *macAutoRequest* is set to TRUE, the entire scan procedure shall terminate when the number of PAN descriptors stored equals the implementation-specified maximum or every channel in the set of available channels has been scanned. If *macAutoRequest* is set to FALSE, the entire scan procedure shall only terminate when every channel in the set of available channels has been scanned.

6.4.2 Starting and realigning a PAN

6.4.2.1 General

This subclause specifies procedures for the PAN coordinator starting a PAN, coordinators realigning a PAN, and devices being realigned on a PAN.

6.4.2.2 Starting a PAN

A PAN should be started by a device only after having first performed a MAC sublayer reset, by issuing the MLME-RESET.request primitive, as described in 8.2.6.2, with the SetDefaultPib parameter set to TRUE; an ED channel scan, as described in 10.18; an active channel scan, as described in 10.19; and selecting a PAN ID distinct from PAN IDs received during the active channel scan. The algorithm for selecting a suitable PAN ID from the list of PAN descriptors returned from the active channel scan procedure is out of the scope of this standard. In addition, the device should set *macShortAddress* to a value less than 0xffff.

To start a PAN not using superframe structure the device uses the MLME-START.request primitive, as defined in 8.2.9.2. An example of a message sequence chart for starting a PAN is illustrated in Figure 6-4.

A device is instructed to begin operating a PAN using superframe structure through the use of the MLME-START-SUPERFRAME.request primitive, as defined in 10.2.9.2, with the PanCoordinator parameter set to TRUE and the CoordRealignment parameter set to FALSE.

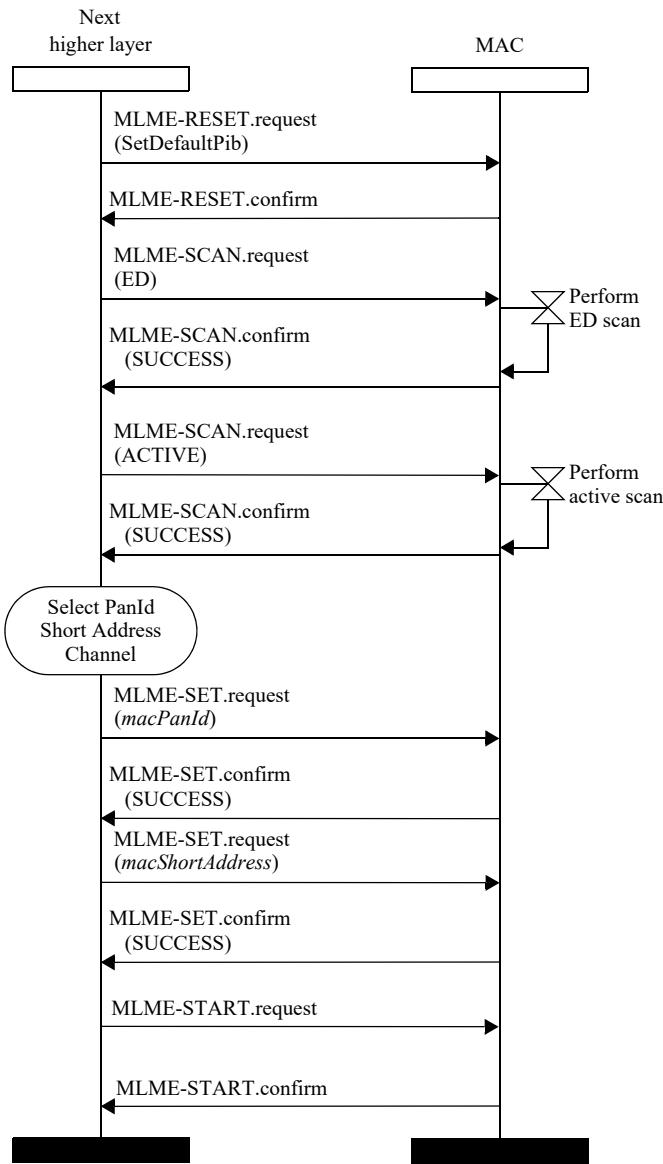


Figure 6-4—PAN start message sequence chart—PAN coordinator

6.5 Synchronization

6.5.1 General

For PANs supporting Beacon frames, synchronization is performed by receiving and decoding the Beacon frames. For PANs not supporting Beacon frames, synchronization is performed by polling the coordinator for data. For more information about synchronization with beacons see 10.2, 10.3, 10.4, or 10.8.

6.5.2 Requesting enhanced beacons

The Enhanced Beacon Request command allows a device to request that a coordinator respond with an Enhanced Beacon containing the requested IEs. Either header or payload IEs may be requested. Header IEs,

Payload IEs, or Nested IEs are requested by sending the desired IE with its Length field set to zero. If the Attribute ID field is empty in the Enhanced Beacon Filter IE and the IEs are not included in the Enhanced Beacon Request, then the responding coordinator shall return an Enhanced Beacon frame. If either are present and the filter criteria are met, the responding coordinator shall return an Enhanced Beacon frame containing the IEs as appropriate. The Enhanced Beacon Filter IE and other IEs shall be passed to a higher layer using the MLME-BEACON-REQUEST.indication primitive provided that the recipient has *macBeaconAutoRespond* set to FALSE.

When an Enhanced Beacon frame is generated in response to an Enhanced Beacon Request command that contained Attribute IDs in the Enhanced Beacon Filter IE, as described in 7.4.4.2, the content of the Enhanced Beacon frame shall include the IEs corresponding to the requested Attribute IDs shown in Table 6-1. A device supporting filtering by the Attribute ID listed in the first column shall also support the IEs in the IEs to include column in Table 6-1. When generated in response to an Enhanced Beacon Request command that contained a request for IEs, as described in 7.5.3, the Enhanced Beacon frame shall also contain the requested IEs.

Table 6-1—Enhanced Beacon Request command IEs per enabled attribute

Attribute ID	PIB attribute	IEs to include
0	<i>macTrleEnabled</i>	TRLE Descriptor IE (10.37.5.1.1)
1	<i>macTschEnabled</i>	TSCH Synchronization IE (10.3.9.1), TSCH Slotframe and Link IE (10.3.9.2), TSCH Timeslot IE (10.3.9.3), Channel Hopping IE (10.16.2.1)
2	<i>macDsmeEnabled</i>	DSME PAN Descriptor IE (10.4.11.1)
3	<i>macLeEnabled</i>	CSL IE (10.5.5.1), RIT IE (10.6.5.1)
4	<i>macHoppingEnabled</i>	Hopping Timing IE (10.5.6.1), Channel Hopping IE (10.16.2.1)
5	<i>macDaEnabled</i>	DA IE (10.24.2.1)
6	<i>macMpmIe</i>	Coexistence Specification IE (10.9.4.1)
7–23	—	Reserved

6.5.3 Timestamps

Several MLME primitives include a Timestamp parameter to indicate when the frame was received.

The timestamp value shall be that of the local clock of the device at the time of the symbol boundary. The timestamp is intended to be a relative time measurement that may or may not be made absolute, at the discretion of the implementer.

The timestamp counter value will roll over to zero after reaching its maximum value representable.

For non-ERDEV, the timestamps will be expressed in symbol periods. The symbol boundary is described by *macSyncSymbolOffset*, as described in Table 8-35. This is a minimum of 24-bit value, and the precision of this value shall be a minimum of 20 bits, with the lowest 4 bits being the least significant.

For ERDEV, timestamps shall be expressed as the time in ranging scheduling time units (RSTU), as defined in 10.29.1.5, corresponding to the start of the received packet (preamble) for the frame.

6.6 Transmission, reception, and acknowledgment

6.6.1 Transmission

Each device shall keep three separate sequence numbers: data sequence number (DSN) stored in *macDsn* and used when generating Data, Multipurpose, or MAC Command frames with Sequence Number field; beacon sequence number (BSN) stored in *macBsn* and used when generating Beacon frames; and enhanced beacon sequence number (EBSN) stored in *macEbsn* and used when generating Enhanced Beacon frames. These sequence numbers are initialized to random values, and stored in their associated MAC PIB attributes. Each time a frame is generated, the MAC sublayer shall copy the value of the related MAC PIB attribute into a Sequence Number field of the MHR of the outgoing frame and then increment the relevant MAC PIB attribute by one. The sequence numbers stored in the MAC PIB attributes shall roll over to zero after reaching the maximum value representable. Each device shall generate exactly one Sequence Number regardless of the number of unique devices with which it wishes to communicate.

NOTE—The DSN is an 8-bit value and, therefore, it is only useful to tie data and Imm-Ack together.

The Source Address field, if present, shall contain the address of the device sending the frame. When a device has associated and has been allocated a short address (i.e., *macShortAddress* is not equal to 0xffff or 0xffff), it should use that address in preference to its extended address (i.e., *macExtendedAddress*) wherever possible. When a device has not yet associated to a PAN, it shall use its extended address in all communications requiring the Source Address field. If the Source Address field is not present, the originator of the frame shall be assumed to be the PAN coordinator, and the Destination Address field shall contain the address of the recipient.

The Destination Address field, if present, shall contain the address of the intended recipient of the frame, which may be either a short address or an extended address. If the Destination Address field is not present, the recipient of the frame shall be assumed to be the PAN coordinator (unless *macImplicitBroadcast* is set to TRUE on the receiver), and the Source Address field shall contain the address of the originator.

The PAN ID compression field, the Source PAN ID field, and the Destination PAN ID field are set as indicated in 7.2.2.6.

If the frame is to be transmitted on a PAN not using periodic beacons, the frame shall be transmitted following the successful application of the unslotted version of the CSMA-CA algorithm, as described in 6.3.2.

If the transmission is direct and originates due to a primitive issued by the next higher layer and the CSMA-CA algorithm fails, the next higher layer shall be notified. If the transmission is indirect and the CSMA-CA algorithm fails, the frame shall remain in the transaction queue until it is requested again and successfully transmitted or until the transaction expires.

The device shall process the frame using the outgoing frame security procedure described in 9.2.2.

If the Status from the outgoing frame security procedure is not SUCCESS, the MLME shall issue the corresponding confirm or MLME-COMM-STATUS.indication primitive with the Status parameter set to the status from the outgoing frame security procedure, indicating the error, and shall not transmit the frame.

If the Status from the outgoing frame security procedure is SUCCESS, the MAC sublayer shall transmit the frame.

6.6.2 Reception and rejection

Each device may choose whether the MAC sublayer is to enable its receiver during idle periods. During these idle periods, the MAC sublayer shall still service transceiver task requests from the next higher layer. A transceiver task shall be defined as a transmission request with acknowledgment reception, if required, or a reception request. On completion of each transceiver task, the MAC sublayer shall request that the PHY enables or disables its receiver, depending on the values of *macBeaconOrder* and *macRxOnWhenIdle*. If *macBeaconOrder* is less than 15, the value of *macRxOnWhenIdle* shall be considered relevant only during idle periods of the CAP of the incoming superframe. If *macBeaconOrder* is equal to 15, the value of *macRxOnWhenIdle* shall be considered relevant at all times.

Due to the nature of radio communications, a device with its receiver enabled will be able to receive and decode transmissions from all devices complying with this standard that are currently operating on the same channel and are in its radio communications range, along with interference from other sources. The MAC sublayer will, therefore, be able to filter incoming frames and send only the frames that are of interest to the next higher layer.

The MAC sublayer shall discard all received frames that do not contain a correct value in their frame check sequence (FCS) field in the MFR, as described in 7.2.11. The FCS field shall be verified on reception by recalculating the purported FCS over the MHR and MAC payload of the received frame and by subsequently comparing this value with the received FCS field. The FCS field of the received frame shall be considered to be correct if these values are the same and incorrect otherwise.

If the MAC sublayer is currently performing a scan, the MAC sublayer shall process all frames received as described in the relevant subclause of 6.4.1.

If the MAC sublayer is not currently performing a scan, it shall accept only frames that satisfy all of the following filtering requirements:

- a) The Frame Type field shall not contain a reserved frame type.
- b) The Frame Version field shall not contain a reserved value.
- c) If a destination PAN ID is included in the frame, it shall match *macPanId* or shall be the broadcast PAN ID.
- d) The Destination Address field shall satisfy one of the following conditions:
 - 1) A short destination address is included in the frame, and it matches either *macShortAddress* or the broadcast address.
 - 2) An extended destination address is included in the frame and matches either *macExtendedAddress* or, if *macGroupRxMode* is set to TRUE, a 64-bit group address, as defined in IEEE Std 802.
 - 3) The Destination Address field and the Destination PAN ID field are not included in the frame, and *macImplicitBroadcast* is TRUE.
 - 4) The device is the PAN coordinator, only source addressing fields are included in a Data frame or MAC command and the source PAN ID matches *macPanId*.
 - 5) The device is the PAN coordinator, only source addressing field is included in a Multipurpose frame and the destination PAN ID matches *macPanId*.
- e) If the frame type indicates that the frame is a Beacon frame and the source PAN ID is present, the source PAN ID shall match *macPanId* unless *macPanId* is equal to the broadcast PAN ID, in which case the Beacon frame shall be accepted regardless of the source PAN ID.

If all of the filtering requirements are satisfied, the frame shall be considered valid and processed further.

When PSDU fragmentation is in use, the acknowledgment of fragments uses the procedure described in 23.3.

For valid frames that are not broadcast, if the Frame Type field indicates a Data frame or MAC command with the Frame Version field set to 0b00–0b01 and the acknowledgment request (AR) field is set to request an acknowledgment, the MAC sublayer shall send an Imm-Ack frame. Prior to the transmission of the Imm-Ack frame, the value of the Sequence Number field included in the received Data frame or MAC command shall be used for the value of the Sequence Number field of the Imm-Ack frame. This step will allow the transaction originator to know that it has received the appropriate Imm-Ack frame.

For valid frames that are not broadcast, if the Frame Type field indicates one of a Multipurpose frame, a Data frame with the Frame Version field set to 0b10, or a MAC command with the Frame Version field set to 0b10, and the AR field is set to request an acknowledgment, the MAC sublayer shall send an Enh-Ack frame unless the device performs the incoming frame security procedure, as defined in 9.2.4. If the device performs the incoming frame security procedure and the Status is not SUCCESS, the device is not required to send an Enh-Ack frame. If the Enh-Ack frame contains IEs and/or a Frame Payload and it is in response to a secured frame, then the Enh-Ack frame shall be secured. If the Enh-Ack frame is in response to a secured frame and does not contain either IEs or a Frame Payload, then the Enh-Ack may be secured.

If the Source PAN ID field is not included in the frame and the Destination PAN ID field is included in the frame, the MAC sublayer shall use the value of the Destination PAN ID field as the source PAN ID.

The device shall process the frame using the incoming frame security procedure described in 9.2.4, if the Security Enabled field is set to one, or 9.2.5, if the Security Enabled field is set to zero.

If the Status from the incoming frame security procedure is not SUCCESS, the MLME shall issue the corresponding confirm or MLME-COMM-STATUS.indication primitive with the Status parameter set to the status from the incoming frame security procedure, indicating the error, and with the security-related parameters set to the corresponding parameters returned by the unsecuring process.

All IEs received in a valid frame that are marked as PASSED in the IeStatusList by the incoming frame security procedure shall be processed by the MAC sublayer, and if required, passed to the next higher layer. If any of the IEs in a valid frame were marked as FAILED, then those IEs are not passed to next higher layer, or processed by the MAC, but MLME shall issue an MLME-COMM-STATUS.indication primitive with the Status parameter set to IMPROPER_IE_SECURITY.

If the valid frame is a Data frame or Multipurpose frame and the status from the incoming frame security procedure is SUCCESS, the MAC sublayer shall pass the MAC service data unit (MSDU) to the next higher layer.

In the case of a high rate pulse repetition frequency UWB PHY based enhanced ranging capable device (HRP-ERDEV) configured to use scrambled timestamp sequence packet configuration option three (SP3) format packets (where the packet does not include an MHR, MFR, PHR, or data payload) the reception of a packet shall be treated differently from a normal data packet. For an unintended recipient expecting a normal data packet, the lack of PHR in the received packet shall cause the MAC sublayer to discard the received packet. For a receiver expecting an SP3 packet, depending on the implementer's choice, the MAC or PHY sublayer shall either accept the received packet if and only if the scrambled timestamp sequence (STS) in the received frame matches the expected STS, or accept the received packet and notify the next higher layer of its arrival with the RangingStsFom set accordingly. In the latter case the higher layers can reject the packet if the STS in the received packet does not match the expected STS. The packet is processed without conducting any of the filtering described in this subclause.

6.6.3 Use of acknowledgments and retransmissions

6.6.3.1 General

A Data frame or MAC command shall be sent with the AR field set appropriately for the frame. A Beacon frame or Ack frame shall always be sent with the AR field set to indicate no acknowledgment requested. Similarly, any frame that is broadcast or has a group address as the extended destination address, as defined in IEEE Std 802, shall be sent with its AR field set to indicate no acknowledgment requested.

6.6.3.2 No acknowledgment

A frame transmitted with its AR field set to indicate no acknowledgment requested, as defined in 7.2.2.5, shall not be acknowledged by its target. The originating device shall assume that the transmission of the frame was successful.

The message sequence chart in Figure 6-5 shows the scenario for transmitting a single frame of data from an originator to a target without requiring an acknowledgment.

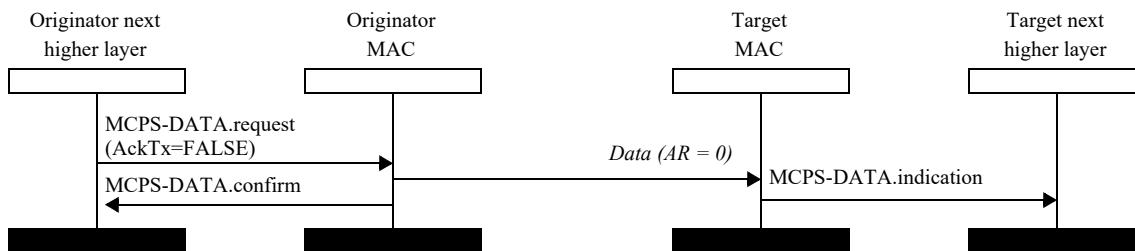


Figure 6-5—Successful data transmission without an acknowledgment

6.6.3.3 Acknowledgment

If the intended recipient received a valid frame, as defined in 6.6.2, with the AR field set to request an acknowledgment, it shall generate and send an Ack frame, as defined in 6.6.2.

The AR field shall be set to no acknowledgment when using Frak as defined in 23.3.

The transmission of an Ack frame outside the CAP shall commence AIFS after the reception of the last symbol of the Data frame or MAC command. The transmission of an Ack frame in the CAP shall commence either AIFS after the reception of the last symbol of the Data frame or MAC command or at a backoff period boundary. In the latter case, the transmission of an Ack frame shall commence between AIFS and (AIFS + $macUnitBackoffPeriod$) after the reception of the last symbol of the Data frame or MAC command. The value of AIFS is 1 ms for the SUN PHYs, LECIM PHYs, or TVWS PHYs. The value of AIFS is equal to $macSifsPeriod$ for all other PHYs.

The receiving device may include additional content in an Enh-Ack frame using IEs. If the originator does not understand a specific IE in the Enh-Ack frame, that IE is ignored, but the transmission is considered successful. The number and the content of the IEs included in the Enh-Ack should be limited to only those IEs with the minimal content that is required.

In the case where the Ack frame may violate the transmission timing restriction defined in 6.6.4, the device shall use the default SHR and PHR lengths defined for that PHY when sending the Ack frame.

The message sequence chart in Figure 6-6 shows the scenario for transmitting a single Data frame from an originator to a recipient with an acknowledgment requested.

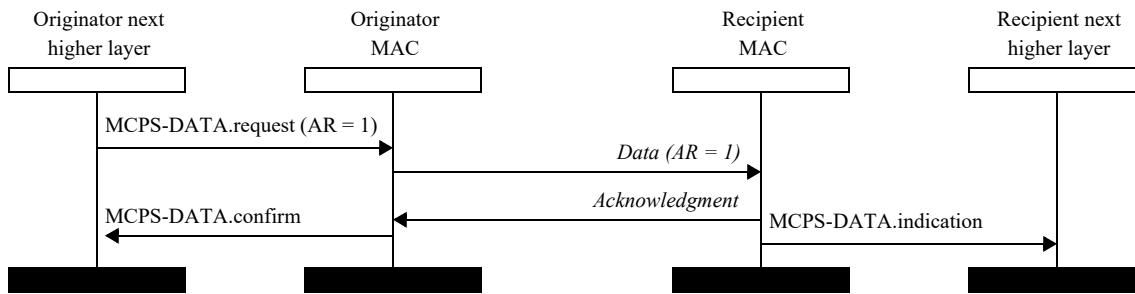


Figure 6-6—Successful data transmission with an acknowledgment

For TVWS ranging-capable devices (RDEVs), the Enh-Ack frame shall include the Timestamp Difference IE as defined in 10.7.3.10 if the Ranging field of the PHR is set to one in the frame being acknowledged.

The acknowledgment transmission in response to a ranging frame (RFRAME) shall be an RFRAME.

6.6.3.4 Retransmissions

A device that sends a frame with the AR field set to indicate no acknowledgment requested may assume that the transmission was successfully received and shall not perform the retransmission procedure.

A device that sends a frame with its AR field set to acknowledgment requested shall wait for the corresponding Ack frame to be received. If an Ack frame is received within the expected time and contains the same DSN, if present, as the original transmission, the transmission is considered successful, and no further action regarding retransmission shall be taken by the device. If an Ack frame is not received within the expected time or the Ack frame that is received contains a DSN that was not the same as the original transmission, the device shall conclude that the single transmission attempt has failed.

If a single transmission attempt has failed and the transmission was indirect, the coordinator shall not retransmit the frame. Instead, the frame shall remain in the transaction queue of the coordinator and can only be extracted following the reception of a new Data Request command. If a new Data Request command is received, the originating device shall transmit the frame using the same DSN as was used in the original transmission.

If a single transmission attempt has failed and the transmission was direct, the device shall repeat the process of transmitting the frame and waiting for the acknowledgment, up to a maximum of *macMaxFrameRetries* times. The retransmitted frame shall contain the same DSN as was used in the original transmission. Each retransmission shall only be attempted if it can be completed within the same portion of the superframe, i.e., the CAP or a GTS in which the original transmission was attempted. If this timing is not possible, the retransmission shall be deferred until the same portion in the next superframe. If an acknowledgment is still not received after *macMaxFrameRetries* retransmissions, the MAC sublayer shall assume the transmission has failed and notify the next higher layer of the failure.

When not using TSCH mode and a frame with the Security Enabled field set to one is retransmitted, the frame shall be retransmitted without changes and without passing through the outgoing frame security procedure, as defined in 9.2.2.

6.6.4 Transmission timing restrictions

In PANs using periodic beacons, certain times may be allocated to devices for transmission. These times are referred to as the allowed transmission interval (ATI). Examples of these include the following:

- *GTS*: Start and end time defined by GTS Info field in the beacon
- *Beacon transmission*: Start time defined by the superframe duration in a PAN using superframe structure
- *TSCH timeslot*: Start and end time defined by the *macSlotframeHandle*, *macTimeslot*, and *macTsTimeslotLength*
- *DSME timeslot*: Start and end time defined in the DSME GTS Response command

The transmission of frames and the associated Ack frames need to be completed at least one SIFS time before the end of the ATI. A SIFS is required prior to the end of the ATI for the device transmitting or receiving the final frame to switch to receiving or transmitting, respectively, in the event that the device is required to switch.

Devices shall also allow for the guard time, as defined in 6.6.5, when calculating the end of the ATI.

Accordingly, the following rules apply:

- 1) For frames that do not request acknowledgment, the transmitting device shall not send the frame if the time required for the frame transmission and a SIFS is greater than the time remaining before the end of the allowed transmission time.
- 2) For frames that request acknowledgment, the transmitting device shall not send the frame if the time required for frame transmission plus the AIFS plus the minimum duration Ack frame plus a SIFS is greater than the time remaining before the end of the allowed transmission time. Note that the minimum required Ack frame duration is for the appropriate Ack frame (Imm-Ack or Enh-Ack) including only the required IEs (e.g., the Time Synchronization IE in TSCH mode), security overhead (if appropriate), and the SHR and PHR duration. If the SHR and/or PHR of a PHY is variable, the PHY defines a default SHR and PHR duration and that value shall be used in the calculation.

6.6.5 Guard time

Guard times are required to keep transmissions in adjacent ATIs, as defined in 6.6.4, from colliding. In addition, as described in 6.6.4, a SIFS time is required to provide sufficient turnaround time between ATIs. Guard time is the time between the end of one ATI and the next ATI. Figure 6-7 is an illustration of the allocation of the guard time such that the ATIs are separated by at least a SIFS if the devices allowed to transmit in adjacent ATIs drift in time towards each other.

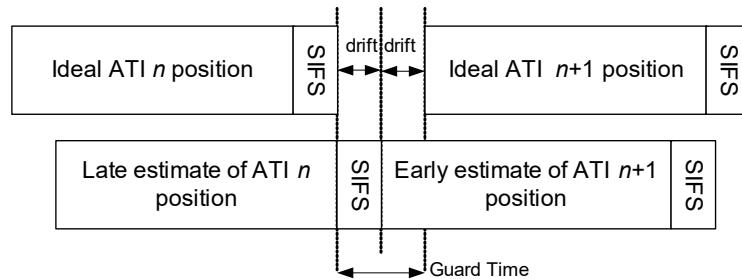


Figure 6-7—Guard time

The required guard time depends on the maximum drift between a device's local time and the ideal time. This drift is a function of the time elapsed since a synchronizing reference event. In a PAN using periodic beacons, the synchronizing event is the start of the preamble of a beacon. In a TSCH PAN the synchronizing event is a Timing Correction IE received from a timekeeping neighbor.

The maximum drift, MaxDrift, may be calculated as follows:

$$MaxDrift = [\text{Clock accuracy}] \times \text{time elapsed since the last synchronizing event}$$

NOTE—While propagation delay also affects timing uncertainty, for this standard it is ignored when calculating the guard time.

Figure 6-8 illustrates the example of a device transmitting frames with no acknowledgment requested, and including the guard time.

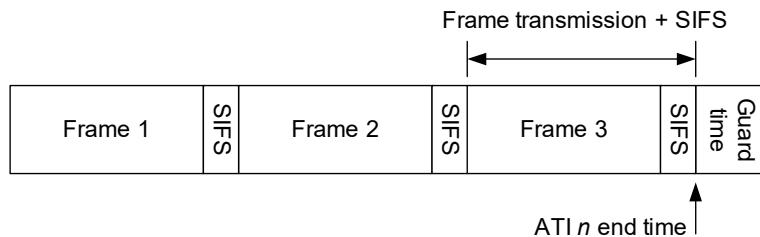


Figure 6-8—SIFS and guard time at the end of an ATI—no Ack requested

Figure 6-9 illustrates the example of a device sending multiple frames with the ACK frame following an AIFS after the frame requesting the ACK frame, and including the guard time.

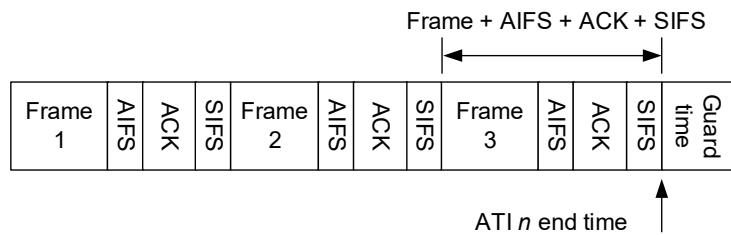


Figure 6-9—AIFS, ACK, SIFS, and guard time at the end of an ATI—Ack requested

Figure 6-10 illustrates the example of a device transmitting frames just prior to scheduled beacon transmission including the guard time.

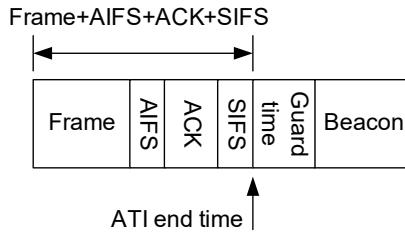


Figure 6-10—Guard time at the end of a superframe

6.6.6 Transmission scenarios

Due to the imperfect nature of the radio medium, a transmitted frame does not always reach its intended destination. There are three different transmission scenarios:

- *Successful data transmission*: The originator MAC sublayer transmits the Data frame to the recipient via the PHY data service. The recipient MAC sublayer receives the Data frame, sends an

acknowledgment back to the originator, and passes the Data frame to the next higher layer. The originator MAC sublayer receives the acknowledgment from the recipient within the expected time. The data transfer is now complete, and the originator MAC sublayer issues a success confirmation to the next higher layer. This sequence of messages for successful data transmission is illustrated in Figure 6-11.

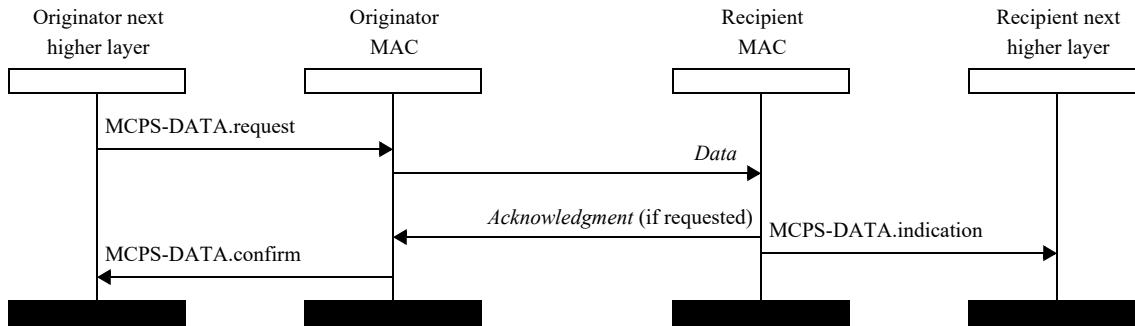


Figure 6-11—Successful data transmission sequence

- *Lost Data frame:* The originator MAC sublayer transmits the Data frame to the recipient via the PHY data service. The recipient MAC sublayer does not receive the Data frame and so does not respond with an acknowledgment. The acknowledgment is not received within the expected time and therefore the data transfer has failed. If the transmission was direct, the originator retransmits the data, and this entire sequence may be repeated up to a maximum of $macMaxFrameRetries$ times; if a data transfer attempt fails a total of $(1 + macMaxFrameRetries)$ times, the originator MAC sublayer will issue a failure confirmation to the next higher layer. If the transmission was indirect, the Data frame will remain in the transaction queue until either another request for the data is received and correctly acknowledged or until $macTransactionPersistenceTime$ is reached. If $macTransactionPersistenceTime$ is reached, the transaction information will be discarded, and the MAC sublayer will issue a failure confirmation to the next higher layer. The sequence of messages for a lost Data frame is illustrated in Figure 6-12.

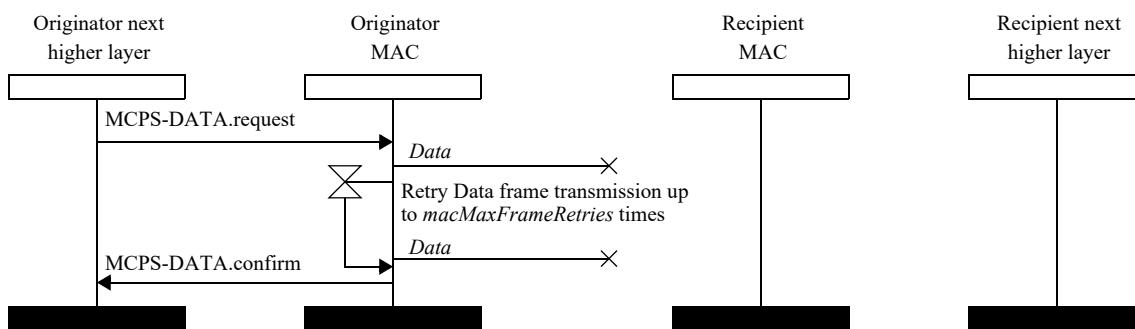


Figure 6-12—Lost Data frame message sequence

- *Lost Ack frame:* The originator MAC sublayer transmits the Data frame to the recipient via the PHY data service. The recipient MAC sublayer receives the Data frame, sends an acknowledgment back to the originator, and passes the Data frame to the next higher layer. The originator MAC sublayer does not receive the Ack frame within the expected time. Therefore, the data transfer has failed. If the transmission was direct, the originator retransmits the Data frame, and this entire sequence may be repeated up to a maximum of $macMaxFrameRetries$ times. If a data transfer attempt fails a total of $(1 + macMaxFrameRetries)$ times, the originator MAC sublayer will issue a failure confirmation to the next higher layer. If the transmission was indirect, the Data frame will remain in the transaction queue either until another request for the data is received and correctly acknowledged or

until $macTransactionPersistenceTime$ is reached. If $macTransactionPersistenceTime$ is reached, the transaction information will be discarded, and the MAC sublayer will issue a failure confirmation to the next higher layer. The message sequence for a lost Ack frame is illustrated in Figure 6-13.

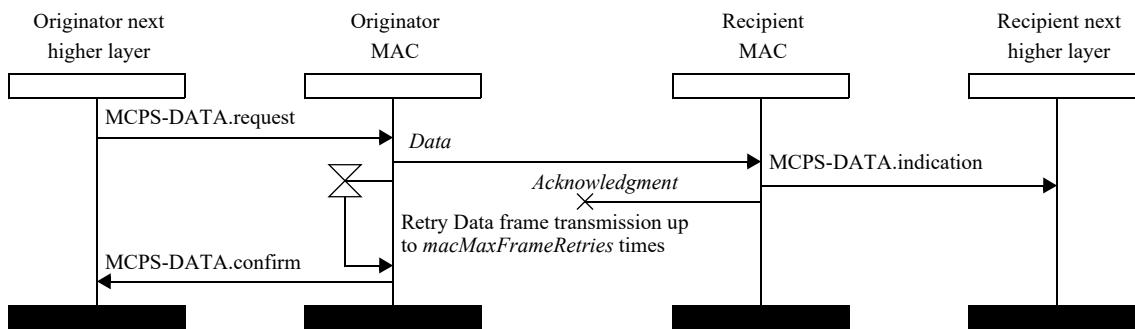


Figure 6-13—Lost acknowledgment message sequence

7. MAC frame formats

7.1 Device extended address

A device's extended address shall be an extended unique identifier (EUI-64), as defined by IEEE Std 802 and assigned by the IEEE Registration Authority.²⁰

The EUI-64 shall be sent in the form defined in 4.5.1.

7.2 General MAC frame format

7.2.1 General

The general MAC frame for Frame Type values other than fragment and extended, as defined in Table 7-1, shall be formatted as illustrated in Figure 7-1.

Octets: 1/2	0/1	0/2	0/2/8	0/2	0/2/8	variable	variable	variable	2/4
Frame Control	Sequence Number	Destination PAN ID	Destination Address	Source PAN ID	Source Address	Auxiliary Security Header	IE		Frame Payload
		Addressing fields					Header IEs	Payload IEs	
MHR							MAC Payload		MFR

Figure 7-1—General MAC frame format

The fields of the MHR appear in a fixed order; however, some fields may not be included in all frames.

If the Frame Type field indicates a Fragment packet or Frak, then the frame shall be formatted as defined in 23.3.4 and 23.3.7.3, respectively.

If the Frame Type field indicates an Extended frame, then the frame shall be formatted as illustrated in 7.3.6.

²⁰ Interested applicants should contact the IEEE Registration Authority, <http://standards.ieee.org/develop/regauth/>.

7.2.2 Frame Control field

7.2.2.1 General

The Frame Control field for frames other than the Multipurpose frame, Fragment frame, and Extended frame shall be formatted as illustrated in Figure 7-2. The Frame Control fields for the Multipurpose frame and Extended frame are specified in 7.3.5 and 7.3.6, respectively.

Bits: 0–2	3	4	5	6	7	8	9	10–11	12–13	14–15
Frame Type	Security Enabled	Frame Pending	AR	PAN ID Compression	Reserved	Sequence Number Suppression	IE Present	Destination Addressing Mode	Frame Version	Source Addressing Mode

Figure 7-2—Format of the Frame Control field

The Fragment frame type does not have a Frame Control field.

7.2.2.2 Frame Type field

The Frame Type field shall be set as defined in Table 7-1.

Table 7-1—Values of the Frame Type field

Frame Type value b2 b1 b0	Description
000	Beacon
001	Data
010	Acknowledgment
011	MAC command
100	Reserved
101	Multipurpose
110	Fragment or Frak ^a
111	Extended

^a The Fragment and Frak formats are defined in 23.3.4 and 23.3.7.3, respectively.

Frame formats for each of the Frame Type field values are specified in 7.3.

7.2.2.3 Security Enabled field

The Security Enabled field shall be set to one if the frame is protected by the MAC sublayer and shall be set to zero otherwise. The Auxiliary Security Header field of the MHR shall be present only if the Security Enabled field is set to one.

7.2.2.4 Frame Pending field

The Frame Pending field shall be set to one if the device sending the frame has more data for the recipient, as described in 10.22. This field shall be set to zero otherwise.

When operating in LE CSL mode, the frame pending bit may be set as described in 10.5.3.

When operating in TSCH mode, the frame pending bit can only be set if there is not a link scheduled in the following timeslot as described in 10.3.2.3.

At all other times, the frame pending bit shall be set to zero on transmission and ignored on reception.

7.2.2.5 Acknowledgment request (AR) field

The AR field specifies whether an acknowledgment is required from the recipient device on receipt of a Data frame or MAC command. If this field is set to one, the recipient device shall send an Ack frame, but only if, additionally, the frame passes the filtering described in 6.6.2. If this field is set to zero, the recipient device shall not send an Ack frame.

7.2.2.6 PAN ID Compression field

The PAN ID Compression field is used to indicate the presence of the PAN ID field.

When the frame version field value is 0b00 or 0b01, the PAN ID compression field is interpreted as follows:

- If both destination and source addressing information is present, the MAC sublayer shall compare the destination and source PAN identifiers. If the PAN IDs are identical, the PAN ID Compression field shall be set to one, and the Source PAN ID field shall be omitted from the transmitted frame. If the PAN IDs are different, the PAN ID Compression field shall be set to zero, and both Destination PAN ID field and Source PAN ID fields shall be included in the transmitted frame.
- If only either the destination or the source addressing information is present, the PAN ID Compression field shall be set to zero, and the PAN ID field of the single address shall be included in the transmitted frame.

When the frame version field value is 0b10, the PAN ID Compression Field for Beacon frame, Data frame, MAC Command frame, and Ack frame shall be set based on the addressing fields present as defined in Table 7-2. Combinations of destination and source address with destination and source PAN ID and PAN Compression not shown in Table 7-2 shall not be generated.

Table 7-2—PAN ID Compression field value for frame version 0b10

Destination address	Source address	Destination PAN ID	Source PAN ID	PAN ID Compression
Not present	Not present	Not present	Not present	0
Not present	Not present	Present	Not present	1
Present	Not present	Present	Not present	0
Present	Not present	Not present	Not present	1
Not present	Present	Not present	Present	0
Not present	Present	Not present	Not present	1
Extended	Extended	Present	Not present	0

Table 7-2—PAN ID Compression field value for frame version 0b10 (continued)

Destination address	Source address	Destination PAN ID	Source PAN ID	PAN ID Compression
Extended	Extended	Not present	Not present	1
Short ^a	Short ^a	Present	Present	0
Short ^a	Extended	Present	Present	0
Extended	Short ^a	Present	Present	0
Short ^a	Extended	Present	Not present	1
Extended	Short ^a	Present	Not present	1
Short ^a	Short ^a	Present	Not present	1

^aIf both the destination and source addressing information is present and either is a short address, the MAC sublayer shall compare the destination and source PAN IDs and the PAN ID Compression field shall be set to zero if and only if the PAN identifiers are identical.

NOTE 1—In IEEE Std 802.15.4-2003, i.e., frame version 0b00, the PAN ID Compression field is named Intra-PAN, but it is in the same position and has the same effect as the PAN ID Compression field in IEEE Std 802.15.4-2006.

NOTE 2—The PAN ID Compression field is not present in Multipurpose frames.

7.2.2.7 Sequence Number Suppression

When set to one, this field indicates suppression of the Sequence Number field in the frame, and the sequence number shall be omitted. When set to zero, the Sequence Number field is present. If the Frame Version field is 0b00 or 0b01, the Sequence Number Suppression field shall be zero.

7.2.2.8 IE Present field

The IE Present field shall be set to one if IEs are contained in the frame. This field shall be set to zero otherwise. If the Frame Version field is 0b00 or 0b01, the IE Present field shall be zero.

7.2.2.9 Destination Addressing Mode field

The Destination Addressing Mode field shall be set to one of the non-reserved values listed in Table 7-3.

Table 7-3—Valid values of the Destination Addressing Mode and Source Addressing Mode fields

Addressing Mode value b1 b0	Description
00	PAN ID and address fields are not present.
01	Reserved
10	Address field contains a short address (16 bit).
11	Address field contains an extended address (64 bit).

If this field is equal to zero and the Frame Type field specifies a Data frame or MAC command and the Frame Version field is set to 0b00 or 0b01, the Source Addressing Mode field shall be nonzero, implying that the frame is directed to the PAN coordinator with the PAN ID as specified in the Source PAN ID field.

For frames with a Frame Version of 0b10, the destination address or destination PAN ID or both may be omitted.

7.2.2.10 Frame Version field

The Frame Version field is an unsigned integer that specifies the version number corresponding to the frame. For all frame types, the Frame Version field shall be set as described in that subclause.

A summary of the frame versions, and their applicability, for each of the frame types is shown in Table 7-4.

Table 7-4—Frame Version field values

Frame type	Frame Version field value			
	0b00	0b01	0b10	0b11
Beacon	IEEE Std 802.15.4-2003	IEEE Std 802.15.4-2006	IEEE Std 802.15.4	Reserved
Data	IEEE Std 802.15.4-2003	IEEE Std 802.15.4-2006	IEEE Std 802.15.4	Reserved
Acknowledgment	IEEE Std 802.15.4-2003	IEEE Std 802.15.4-2006	IEEE Std 802.15.4	Reserved
MAC Command	IEEE Std 802.15.4-2003	IEEE Std 802.15.4-2006	IEEE Std 802.15.4	Reserved
Reserved	—	—	—	—
Multipurpose	IEEE Std 802.15.4	Reserved	Reserved	Reserved
Fragment	Frame Version field not present in frame			
Extended	Frame Version field not present in frame			

7.2.2.11 Source Addressing Mode field

The Source Addressing Mode field shall be set to one of the values listed in Table 7-3.

If this field is equal to zero and the Frame Type field specifies a Data frame or MAC command, and the Frame Version field is set to 0b00 or 0b01, the Destination Addressing Mode field shall be nonzero, implying that the frame has originated from the PAN coordinator with the PAN ID as specified in the Destination PAN ID field.

7.2.3 Sequence Number field

The Sequence Number field specifies the sequence identifier for the frame.

For a Beacon frame, the Sequence Number field shall specify a BSN. For an Enhanced Beacon frame, the Sequence Number field shall specify an EBSN. For other frames, the Sequence Number field shall specify a DSN.

7.2.4 Destination PAN ID field

The Destination PAN ID field, when present, is an unsigned integer that specifies the unique PAN ID of the intended recipient of the frame. A value of the broadcast PAN ID, as defined in 6.2, in the Destination PAN ID field shall be accepted as a valid PAN ID by all devices currently listening to the channel.

7.2.5 Destination Address field

The Destination Address field, when present, with a length specified in the Destination Addressing Mode field of the Frame Control field as described in 7.2.2.9, specifies the address of the intended recipient of the frame. A value of the broadcast short address, as defined in 6.2, in the Destination Address field shall be accepted as a valid address by all devices currently listening to the channel.

This field shall be included in the MAC frame only if the Destination Addressing Mode field is nonzero.

7.2.6 Source PAN ID field

The Source PAN ID field, when present as described in 7.2.2.6, specifies the unique PAN ID of the originator of the frame.

The PAN ID of a device is initially determined during association on a PAN but may change following a PAN ID conflict resolution, as described in 10.17.

7.2.7 Source Address field

The Source Address field, when present, specifies the address of the originator of the frame. This field shall be included in the MAC frame only if the Source Addressing Mode field is nonzero.

7.2.8 Auxiliary Security Header field

The Auxiliary Security Header field specifies information required for security processing. This field shall be present only if the Security Enabled field is set to one. The formatting of the Auxiliary Security Header field is described in 9.4.

7.2.9 IE field

The IE field is variable length and contains one or more IEs. This field is composed of the Header IE and Payload IE subfields. This field shall be present only if the IE Present field in the Frame Control field is set to one. The format of the IE field is shown in Figure 7-3. Each IE consists of a descriptor and an optional payload as described in 7.4. This standard does not limit the number of IEs within the IE field.

Header IEs, if present, follow the Auxiliary Security Header and are part of the MHR. Header IEs, if present, may require termination, as defined in 7.4.1.

Payload IEs, if present, follow the MHR and are considered part of the MAC payload, i.e., they may be encrypted. A set of payload IEs may require termination, as described in 7.4.1.

Octets: variable	...	variable	0/2	variable	...	variable	0/2
Header IE #1	...	Header IE #n	Header Termination IE	Payload IE #1	...	Payload IE #m	Payload Termination IE

Figure 7-3—Format of IE field

7.2.10 Frame Payload field

The Frame Payload field contains information specific to individual frame types. If the Security Enabled field is set to one, the frame payload of the frame may be cryptographically protected, as described in Clause 9.

7.2.11 FCS field

The FCS field contains a 16-bit ITU-T CRC or a 32-bit CRC equivalent to ANSI X3.66-1979.²¹ The FCS is calculated over the MHR and MAC payload parts of the frame; these parts together are referred to as the calculation field. On certain PHYs the type of FCS field depends on the *macFcsType* attribute.

The MAC may optionally employ the 4-octet FCS with the HRP UWB PHY in higher pulse repetition frequency (HPRF) mode, but in all other HRP UWB PHY modes shall employ the 2-octet FCS.

Devices compliant with one or more of the SUN PHYs or TVWS PHYs shall implement the 4-octet FCS.

Devices compliant with the MSK PHY implementing the 2000 kb/s data rate shall implement both the 2-octet and 4-octet FCS, as indicated by the contents of the Extended PHR field described in 18.1.3. If the Extended PHR field is set to one, the 4-octet FCS shall be used; if the Extended PHR field is set to zero, the 2-octet FCS shall be used.

The 2-octet FCS shall be calculated using the following standard generator polynomial:

$$G_{16}(x) = x^{16} + x^{12} + x^5 + 1$$

The 2-octet FCS shall be calculated for transmission using the following algorithm:

- Let $M(x) = b_0x^{k-1} + b_1x^{k-2} + \dots + b_{k-2}x + b_{k-1}$ be the polynomial representing the sequence of bits for which the checksum is to be computed.
- Multiply $M(x)$ by x^{16} , giving the polynomial $x^{16} \times M(x)$.
- Divide $x^{16} \times M(x)$ modulo 2 by the generator polynomial, $G_{16}(x)$, to obtain the remainder polynomial, $R(x) = r_0x^{15} + r_1x^{14} + \dots + r_{14}x + r_{15}$
- The FCS field is given by the coefficients of the remainder polynomial, $R(x)$.

Here, binary polynomials are represented as bit strings, in highest polynomial degree first order.

As an example, consider an Ack frame with no payload and the following 3-octet MHR:

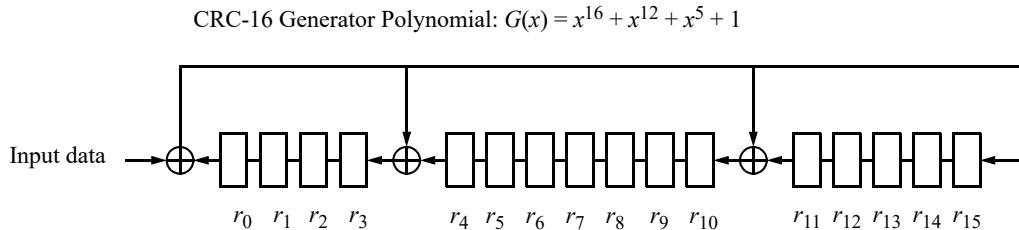
0100 0000 0000 0000 0101 0110	[leftmost bit (b_0) passed to the PHY first in time]
$b_0 \dots \dots \dots b_{23}$	

The FCS for this case would be the following:

0010 0111 1001 1110	[leftmost bit (r_0) passed to the PHY first in time]
$r_0 \dots \dots \dots r_{15}$	

²¹ Information on references can be found in Clause 2.

A typical implementation is depicted in Figure 7-4.



1. Initialize the remainder register (r_0 through r_{15}) to zero.
2. Shift MHR and payload into the divider in the order that they are passed to the PHY.
3. After the last bit of the data field is shifted into the divider, the remainder register contains the FCS.
4. The FCS is appended to the data field so that r_0 is passed to the PHY first.

Figure 7-4—Typical 2-octet FCS implementation

The 4-octet FCS is calculated using the following standard generator polynomial of degree 32:

$$G_{32}(x) = x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} + x^{10} + x^8 + x^7 + x^5 + x^4 + x^2 + x + 1$$

The 4-octet FCS is the one's complement of the (modulo 2) sum of the two remainders in a) and b):

- a) The remainder resulting from $[(x^k \times (x^{31} + x^{30} + \dots))]$ divided (modulo 2) by $G_{32}(x)$, where the value k is the number of bits in the calculation field.
- b) The remainder resulting from the calculation field contents, treated as a polynomial, is multiplied by x^{32} and then divided by $G_{32}(x)$.

At the transmitter, the initial remainder of the division shall be preset to all ones and then modified via division of the calculation field by the generator polynomial $G_{32}(x)$. The one's complement of this remainder is the 4-octet FCS field. The FCS field is passed to the PHY commencing with the coefficient of the highest order term.

At the receiver, the initial remainder shall be preset to all ones. The serial incoming bits of the calculation field and FCS, when divided by $G_{32}(x)$ in the absence of transmission errors, result in a unique nonzero remainder value. The unique remainder value is the polynomial shown:

$$x^{31} + x^{30} + x^{26} + x^{25} + x^{24} + x^{18} + x^{15} + x^{14} + x^{12} + x^{11} + x^{10} + x^8 + x^6 + x^5 + x^4 + x^3 + x + 1$$

Upon transmission, if the length of the calculation field is less than 4 octets, the FCS computation shall assume padding the calculation field by appending zero value octets to the most significant bits to make the calculation field length exactly 4 octets; however, these pad bits shall not be transmitted. Upon reception, if the length of the calculation field is less than 4 octets, the received calculation field shall be appended with zero value octets to the most significant bits to make the calculation field length exactly 4 octets prior to computing the FCS for validation.

As an example, consider an Ack frame with no payload and the following 3-byte MHR:

0100 0000 0000 0000 0101 0110	[leftmost bit (b_0) passed to the PHY first in time]
b_0 b_{23}	

Prior to FCS computation, the zero padded calculation field is given as follows:

0100 0000 0000 0000 0101 0110 0000 0000	
b_0 b_{31}	

The 4-octet FCS for this case would be the following:

0101 1101 0010 1001 1111 1010 0010 1000	[leftmost bit (r_0) passed to the PHY first in time]
r_0 r_{31}	

7.3 Format of individual frame types

7.3.1 Beacon frame format

7.3.1.1 Overview

The Beacon frame shall be formatted as illustrated in Figure 7-5.

Octets: 2	1	4/10	variable	2	variable	variable	variable	2/4
Frame Control	Sequence Number	Addressing fields	Auxiliary Security Header	Superframe Specification	GTS Info	Pending Address	Beacon Payload	FCS
MHR				MAC Payload				MFR

Figure 7-5—Beacon frame format

The format of the Beacon frame for Frame Versions 0b00 or 0b01 shall be as illustrated in Figure 7-5. If the Frame Version is 0b00 or 0b01, the Superframe Specification, GTS, and Pending Address fields are always present. If the frame version is 0b10, the IE Present field in the Frame Control field may be set to one to indicate the presence of IEs as described in 7.2.2.8, 7.2.9, and 7.4.

The Enhanced Beacon frame is differentiated from the Beacon by the frame version being set to 0b10. The MAC frame for the Enhanced Beacon frame shall be formatted as illustrated in Figure 7-6.

Octets: 2	0/1	variable	variable	variable	variable	variable	2/4
Frame Control	Sequence Number	Addressing fields	Auxiliary Security Header	IEs		Beacon Payload	FCS
MHR				Header IEs	Payload IEs	MAC Payload	

Figure 7-6—Enhanced Beacon frame format

7.3.1.2 Beacon frame MHR field

The Frame Type field shall contain the value that indicates a Beacon frame, as shown in Table 7-1. The Security Enabled field shall be set to one if security is enabled and the Frame Version field is not zero. If a broadcast frame is pending, the Frame Pending field shall be set to one.

The Sequence Number field shall contain the current value of *macBsn* if it is a Beacon frame or *macEbsn* if it is an Enhanced Beacon frame. Because a device may be sending both Beacon frames and Enhanced Beacon frames, separate sequence numbers shall be maintained. If sending an Enhanced Beacon frame (Frame Version field is 0b10), the sequence number may be suppressed by setting the Sequence Number Suppression field in the Frame Control field. When the frame version field is 0b00–0b01, the Sequence Number field shall be present.

When the Frame Version field is 0b00–0b01:

- The Source Addressing mode field shall be set to indicate that the Source Address and Source PAN ID fields are present.
- The Destination Addressing mode field shall be set to indicate that the Destination Address and Destination PAN ID fields are not present.
- The Source PAN ID field and Source Address field shall contain *macPanId* and the address, respectively, of the device transmitting the beacon.
- All other fields in the Frame Control field shall be set to zero and ignored on reception.

The Auxiliary Security Header field, if present, shall contain the information required for security processing of the Beacon frame, as specified in 7.2.8.

When the Frame Version field is 0b10:

- The MHR may contain a sequence number.
- The MHR may contain any addressing fields supported by the general frame format.
- The Source Address field shall contain the address of the device transmitting the beacon.

If the Enhanced Beacon frame is sent in response to an Enhanced Beacon Request command:

- If a PAN ID is required, then the Destination PAN ID field is set to the value of *macPanId*, and the Source PAN ID field is omitted.
- The Destination Address field shall contain the source address contained in the received Enhanced Beacon Request command.
- The PAN ID Compression field is set as defined in Table 7-2.

7.3.1.3 IEs field

The IEs field may contain IEs as defined in 7.4.

7.3.1.4 Superframe Specification field

The Superframe Specification field shall be formatted as illustrated in Figure 7-7.

Bits: 0–3	4–7	8–11	12	13	14	15
Beacon Order	Superframe Order	Final CAP Slot	BLE	Reserved	PAN Coordinator	Association Permit

Figure 7-7—Format of the Superframe Specification field

The Beacon Order field shall specify the transmission interval of the beacon. The relationship between the beacon order and the beacon interval is explained in 10.2.2.

The Superframe Order field shall specify the length of time during which the superframe is active (i.e., receiver enabled), including the Beacon frame transmission time. The relationship between the superframe order and the superframe duration is explained in 10.2.2.

The Final CAP Slot field specifies the final superframe slot utilized by the CAP. The duration of the CAP, as implied by this field, shall be greater than or equal to the value specified by *aMinCapLength*. However, an exception is allowed for the accommodation of the temporary increase in the Beacon frame length needed to perform GTS maintenance, as described in 7.3.1.5.

The battery life extension (BLE) field shall be set to one if frames transmitted to the beacons device during its CAP are required to start in or before *macBattLifeExtPeriods* full backoff periods after the IFS period following the beacon. Otherwise, the BLE field shall be set to zero.

The PAN Coordinator field shall be set to one if the Beacon frame is being transmitted by the PAN coordinator. Otherwise, the PAN Coordinator field shall be set to zero.

The Association Permit field shall be set to one if *macAssociationPermit* is set to TRUE (i.e., the coordinator is accepting association to the PAN). The association permit bit shall be set to zero if the coordinator is currently not accepting Association Requests on its network.

7.3.1.5 GTS Info field

The GTS Info field shall be formatted as illustrated in Figure 7-8.

Octets: 1	0/1	variable
GTS Specification	GTS Directions	GTS List

Figure 7-8—Format of the GTS Info field

The GTS Specification field shall be formatted as illustrated in Figure 7-9.

Bits: 0–2	3–6	7
GTS Descriptor Count	Reserved	GTS Permit

Figure 7-9—Format of the GTS Specification field

The GTS Descriptor Count field specifies the number of 3-octet GTS descriptors contained in the GTS List field of the Beacon frame. If the value of this field is greater than zero, the size of the CAP shall be allowed to dip below $aMinCapLength$ to accommodate the temporary increase in the Beacon frame length caused by the inclusion of the field. If the value of this field is zero, the GTS Directions field and GTS List field of the Beacon frame are not present.

The GTS Permit field shall be set to one if $macGtsPermit$ is equal to TRUE (i.e., the PAN coordinator is accepting GTS requests). Otherwise, the GTS Permit field shall be set to zero.

The GTS Directions field shall be formatted as illustrated in Figure 7-10.

Bits: 0–6	7
GTS Directions Mask	Reserved

Figure 7-10—Format of the GTS Directions field

The GTS Directions Mask field is a mask identifying the directions of the GTSs in the superframe. The lowest bit in the mask corresponds to the direction of the first GTS contained in the GTS List field of the Beacon frame, with the remainder appearing in the order that they appear in the list. Each bit shall be set to one if the GTS is a receive-only GTS or to zero if the GTS is a transmit-only GTS. GTS direction is defined relative to the direction of the Data frame transmission by the device.

The size of the GTS List field is defined by the values specified in the GTS Specification field of the Beacon frame and contains the list of GTS descriptors that represents the GTSs that are being maintained. The maximum number of GTS descriptors shall be limited to seven.

Each GTS descriptor shall be formatted as illustrated in Figure 7-11.

Bits: 0–15	16–19	20–23
Device Short Address	GTS Starting Slot	GTS Length

Figure 7-11—Format of the GTS descriptor

The Device Short Address field shall contain the short address of the device for which the GTS descriptor is intended.

The GTS Starting Slot field contains the superframe slot at which the GTS is to begin.

The GTS Length field contains the number of contiguous superframe slots over which the GTS is active.

7.3.1.6 Pending Address field

The Pending Address field shall be formatted as illustrated in Figure 7-12.

Octets: 1	variable
Pending Address Specification	Address List

Figure 7-12—Pending Address field format

The Pending Address Specification field shall be formatted as illustrated in Figure 7-13.

Bits: 0–2	3	4–6	7
Number of Short Addresses Pending	Reserved	Number of Extended Addresses Pending	Reserved

Figure 7-13—Format of the Pending Address Specification field

The Number of Short Addresses Pending field indicates the number of short addresses contained in the Address List field of the Beacon frame.

The Number of Extended Addresses Pending field indicates the number of extended addresses contained in the Address List field of the Beacon frame.

The size of the Address List field is determined by the values specified in the Pending Address Specification field. The Address List field contains the set of addresses of the devices that currently have messages pending with the coordinator. The address list shall not contain the broadcast short address.

The maximum number of addresses pending shall be limited to seven and may include both short and extended addresses. All pending short addresses shall appear first in the list followed by any extended addresses. If the coordinator is able to store more than seven transactions, it shall indicate them in its beacon on a first-come-first-served basis, ensuring that the Beacon frame contains at most seven addresses.

7.3.1.7 Beacon Payload field

The Beacon Payload field is an optional sequence of octets to be transmitted, containing the value from *macBeaconPayload* set by the next higher layer.

7.3.2 Data frame format

7.3.2.1 Overview

The Data frame shall be formatted as illustrated in Figure 7-14.

Octets: 2	0/1	variable	variable	variable		variable	2/4
Frame Control	Sequence Number	Addressing fields	Auxiliary Security Header	IEs		Data Payload	FCS
				Header IEs	Payload IEs		
MHR				MAC Payload			MFR

Figure 7-14—Data frame format

7.3.2.2 Data frame MHR field

The Frame Type field shall contain the value that indicates a Data frame, as shown in Table 7-1. The Security Enabled field shall be set to one if security is enabled and the Frame Version field is not zero. All other fields in the Frame Control field shall be set appropriately according to the intended use of the Data frame.

The Sequence Number field, if present, shall contain the current value of *macDsn*. If the frame version is 0b10, the sequence number may be suppressed by setting the Sequence Number Suppression field in the Frame Control field.

The Addressing fields comprise the destination address fields and/or the source address fields, depending on the settings in the Frame Control field.

The Auxiliary Security Header field, if present, shall contain the information required for security processing of the Data frame, as specified in 7.2.8.

If the frame version is 0b10, the IE Present field in the Frame Control field may be set to one to indicate the presence of IEs as described in 7.2.2.8, 7.2.9, and 7.4.

7.3.2.3 Data Payload field

The payload of a Data frame shall contain the sequence of octets that the next higher layer has requested the MAC sublayer to transmit.

7.3.3 Ack frame format

The Ack frame format is used for both an Imm-Ack frame or Enh-Ack frame. The type of Ack frame is determined by the value of the Frame Version field. Frame Version field values of 0b00–0b01 indicate an Imm-Ack frame while a Frame Version field value of 0b10 indicates an Enh-Ack frame.

The Imm-Ack frame shall be formatted as illustrated in Figure 7-15.

Octets: 2	1	2/4
Frame Control	Sequence Number	FCS
MHR		MFR

Figure 7-15—Imm-Ack frame format

The Enh-Ack frame shall be formatted as illustrated in Figure 7-16.

Octets:2	0/1	0/2	0/2/8	0/2	0/2/8	variable	variable	variable	2/4
Frame Control	Sequence Number	Destination PAN ID	Destination Address	Source PAN ID	Source Address	Auxiliary Security Header	IE	Frame Payload	FCS
		Addressing fields					Header IEs	Payload IEs	
		MHR					MAC Payload		MFR

Figure 7-16—Enh-Ack frame format

If the Ack frame is being sent in response to a received Data frame as explained in 10.5.3, the Frame Pending field shall be set as indicated.

If the Ack frame is being sent in response to either a Data frame other than as explained in 10.5.3 or another type of MAC command, the device shall set the Frame Pending field to zero.

The AR field in an Ack frame shall be set to zero.

In an Imm-Ack frame, all other fields in the Frame Control field shall be set to zero.

In an Enh-Ack frame, the other fields in the Frame Control fields shall be set as follows:

- If *macSecurityEnabled* is TRUE, the Security Enabled field shall be set as defined in 6.6.2 and shall be set to zero otherwise.
- The PAN ID compression field and Sequence Number Compression field shall be set to be the same value as the corresponding fields in the Frame Control field of the frame that is being acknowledged.
- The IEs present field shall be set to one if IEs are included in the Enh-Ack frame.
- The Destination Addressing Mode field shall contain the value of the Source Addressing Mode field in the Frame Control field of the frame that is being acknowledged.
- The Source Addressing mode field shall be set as appropriate for the address of the device transmitting the Enh-Ack frame, as described in Table 7-3.

The Source Address field, when present, contains the address of the device originating the Enh-Ack frame. The Source PAN ID field, when present, contains the PAN ID corresponding to the device originating the Enh-Ack frame.

The Destination Address field, when present, shall contain the value of the Source Address field from the frame that is being acknowledged. The Destination PAN ID, when present, contains the value from the Source PAN ID field from the frame that is being acknowledged.

If the Security Enabled field in the Frame Control field is set to one, the Enh-Ack frame is protected using the procedure described in 9.2.2. The SecurityLevel, KeyIdMode, KeySource, and KeyIndex shall be set to match the corresponding fields of the frame that is being acknowledged.

The Sequence Number field, when present shall contain the value of the sequence number received in the frame for which the acknowledgment is to be sent.

7.3.4 MAC Command frame format

7.3.4.1 Overview

The MAC Command frame shall be formatted as illustrated in Figure 7-17.

Octets: 2	0/1	variable	variable	variable		1	variable	2/4
Frame Control	Sequence Number	Addressing fields	Auxiliary Security Header	IE		Command ID	Content	FCS
				Header IEs	Payload IEs			
MHR				MAC Payload			MFR	

Figure 7-17—MAC Command frame format

7.3.4.2 MHR field

The Sequence Number field, if present, shall contain the current value of $macDsn$. If the Frame Version field is 0b10, the sequence number may be suppressed by setting the Sequence Number Suppression field in the Frame Control field. If the Frame Version field is 0b00 or 0b01 the Sequence Number field shall be present.

The addressing fields shall comprise the destination address fields and/or the source address fields, depending on the settings in the Frame Control field. If the Frame Version field is 0b10, then either address may be suppressed.

The Auxiliary Security Header field, if present, shall contain the information required for security processing of the MAC command, as specified in 7.2.8.

If the frame version is 0b10, the IE Present field in the Frame Control field may be set to one to indicate the presence of IEs as described in 7.2.2.8, 7.2.9, and 7.4.

7.3.4.3 Command ID field

The Command ID field identifies the MAC command being used. Valid values of the Command ID field are defined in Table 7-11.

7.3.4.4 Payload field

The Payload field contains the MAC command itself. The formats of the individual commands are described in 7.5.

7.3.5 Multipurpose frame format

7.3.5.1 Overview

The Multipurpose frame type provides a flexible format that may be used for a variety of purposes. The format supports a short and long form of the Frame Control field, and allows for all the fields in the MHR to be present or omitted as specified by the generating service. Multipurpose frames are treated in the same manner as Data frames, and their content is passed to/from the next higher layer using the MAC common part sublayer (MCPS) DATA primitives. Some suggested uses are described in “Application of IEEE Std 802.15.4” [B4].

The multipurpose frame shall be formatted as illustrated in Figure 7-18.

Octets: 1/2	0/1	0/2	0/2/8	0/2/8	variable	variable	variable	2/4
MP Frame Control	Sequence Number	Destination PAN ID	Destination Address	Source Address	Auxiliary Security Header	IE	Frame Payload	FCS
MHR						MAC Payload		MFR

Figure 7-18—Multipurpose frame format

The MP Frame Control field shall be formatted as illustrated in Figure 7-19.

Bits: 0–2	3	4–5	6–7	8	9	10	11	12–13	14	15
Frame Type	Long Frame Control	Destination Addressing Mode	Source Addressing Mode	PAN ID Present	Security Enabled	Sequence Number Suppression	Frame Pending	Frame Version	Ack Request	IE Present

Figure 7-19—Format of the MP Frame Control field

7.3.5.2 Frame Type field

The Frame Type field shall contain the value that indicates a Multipurpose frame, as shown in Table 7-1.

7.3.5.3 Long Frame Control field

The Long Frame Control field shall be set to zero to indicate an MP Short Frame Control field (only bits 0 to 7 in Figure 7-19 make up the field, and bits 8 to 15 are assumed to be zero), and to one to indicate an MP Long Frame Control field (bits 0 to 15 in Figure 7-19 make up the field).

7.3.5.4 Destination Addressing Mode field

The Destination Addressing Mode field shall be set to one of the values listed in Table 7-3. The length of the Destination Address field in the MHR shall correspond to the value of the Destination Addressing Mode field.

7.3.5.5 Source Addressing Mode field

The Source Addressing Mode field shall be set to one of the values listed in Table 7-3. The length of the Source Address field in the MHR shall correspond to the value of the Source Addressing Mode field.

7.3.5.6 PAN ID Present field

The PAN ID Present field is present only if the Long Frame Control field is set to one. It shall be set to one if the destination PAN ID is present in the MHR. Otherwise, it is set to zero and the PAN ID is not present in the MHR.

The Source PAN ID, not present in the frame, is the same as the destination PAN ID.

7.3.5.7 Security Enabled field

The Security Enabled field shall be set to one if the frame is protected by the MAC sublayer and shall be set to zero otherwise.

7.3.5.8 Sequence Number Suppression field

The Sequence Number Suppression field shall be set to one if the Sequence Number field is not to be included in the MHR. Otherwise, it shall be set to zero.

7.3.5.9 Frame Pending field

The Frame Pending field shall be set to one if the device sending the frame has more data for the recipient. This field shall be set to zero otherwise.

7.3.5.10 Frame Version field

The Frame Version field is an unsigned integer that specifies the version number of the frame. This field shall be set to zero.

7.3.5.11 Ack Request field

The Ack Request field shall be set to one if an acknowledgment is required from the recipient device on receipt of a valid frame. Otherwise, it shall be set to zero.

7.3.5.12 IEs Present field

The IEs Present field shall be set to one if IEs are to be included in the frame. Otherwise, it shall be set to zero.

7.3.5.13 Sequence Number field

The Sequence Number field specifies the sequence identifier for the frame, as described in 7.2.3. It is normally present, but can be suppressed using the Sequence Number Suppression field as described in 7.3.5.8.

7.3.5.14 Destination PAN ID field

The Destination PAN ID field specifies the unique PAN ID of the intended recipient of the frame, as described in 7.2.4.

7.3.5.15 Destination Address field

The Destination Address field, when present, specifies the address of the intended recipient of the frame.

7.3.5.16 Source Address field

The Source Address field, when present, specifies the address of the originator of the frame.

7.3.5.17 Auxiliary Security Header field

The Auxiliary Security Header field specifies information required for security processing, including how the frame is actually protected (security level) and which keying material from the MAC security PIB is used, as defined in 9.5. This field shall be present only if the Security Enabled field is set to one. For details on formatting, refer to 9.4.

7.3.5.18 IEs field

The IEs field is present if the IEs Present field is set to one. The format of IEs is specified in 7.4. Each type of IE is terminated as required per 7.4.1.

7.3.5.19 Payload field

The Payload field has a variable length and contains unformatted (not in an IE) payload.

7.3.6 Extended frame format

The Extended frame shall be formatted as illustrated in Figure 7-20.

Bits: 0–2	3–5	variable
Frame Type	Extended Frame Type	Extended Frame Payload

Figure 7-20—Extended frame format

The Frame Type field is defined in 7.2.2.2.

The Extended Frame Type field is used to specify additional frame types by adding additional bits to the Frame Type field. Valid values of the Extended Frame Type field are given in Table 7-5.

Table 7-5—Extended Frame Type values

Extended Frame Type b5 b4 b3	Description
000–011	Reserved
111	Assigned to Telecommunications Industry Association (TIA)

The Extended Frame Payload field is defined by the frame type indicated by the Extended Frame Type field or by the organization to which the Extended Frame Type has been assigned. Currently, this standard does not have any frame formats defined for the reserved values of Extended Frame Type fields.

7.4 IEs

7.4.1 IE list termination

When determining if a termination of the Header IEs or Payload IEs is required, the authentication or encryption procedures are not taken into account. Table 7-6 lists the rules for the inclusion of termination IEs. In the table, HT1 refers to Header Termination 1 IE, as defined in 7.4.2.4, while HT2 refers to Header Termination 2 IE, as defined in 7.4.2.5.

NOTE—A header termination IE is required prior to the payload IEs because the payload IEs might be encrypted, and then it is not possible to detect where the header IEs end and the payload IEs begin.

Table 7-6—Termination IE inclusion rules

Header IEs present	Payload IEs present	Data Payload present	Header Termination IE included	Payload Termination IE included	Notes
No	No	No	None	None	No IE lists present, hence no termination. Included here for completeness.
Yes	No	No	None	None	No termination is required because the end of the frame can be determined from the frame length and FCS length.
No	Yes	No	HT1 required	Optional	Header Termination IE 1 is required to signal end of the MHR and beginning of the Payload IE list.
Yes	Yes	No	HT1 required	Optional	Header IE Termination 1 is required while the Payload IE Termination is not required, but is allowed.
No	No	Yes	None	None	No IE lists present, hence no termination. Included here for completeness.
Yes	No	Yes	HT2 required	None	Header Termination IE 2 is used to signal end of the MHR and beginning of the MAC Payload.
No	Yes	Yes	HT1 required	Required	—
Yes	Yes	Yes	HT1 required	Required	—

7.4.2 Header IEs

7.4.2.1 Header IE format

The Header IE shall be formatted as illustrated in Figure 7-21.

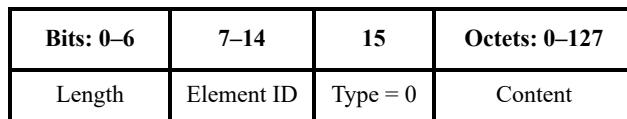


Figure 7-21—Format of Header IEs

The Length field specifies the number of octets in the Content field.

The Element IDs are defined in Table 7-7 for each of the Header IEs. In the table, an X in the column for a frame type indicates that the IE may be used in that frame. If there is not an X in the column, then the IE shall not be used in that frame. In the table, UL refers to the layers above the MAC.

Table 7-7—Element IDs for Header IEs

Element ID	Name	Enhanced Beacon	Enhanced ACK	Data	Multipurpose	MAC command	Format subclause	Use description	Used by	Created by
0x00	Vendor Specific Header IE	X	X	X	X	X	7.4.2.2	—	UL	UL
0x01–0x19	Reserved									
0x1a	CSL IE	X	X	X	X	X	10.5.5.1	10.5.4	MAC	MAC
0x1b	RIT IE	X		X		X	10.6.5.1	10.6	MAC	MAC
0x1c	DSME PAN Descriptor IE	X					10.4.11.1	10.4	UL, MAC	UL
0x1d	Rendezvous Time IE		X		X		10.5.5.2	10.5	MAC	MAC
0x1e	Time Correction IE		X				10.3.8.1	10.3.5.2, 6.6.3.3	MAC	MAC
0x1f–0x20	Reserved									
0x21	Extended DSME PAN Descriptor IE	X					10.4.11.2	10.4	UL, MAC	UL
0x22	Fragment Sequence Context Description (FSCD) IE				X	X	10.15.2.1	24.4.2.1	MAC	MAC
0x23	Simplified Superframe Specification IE	X					10.2.8.1	10.2, [B4]	MAC	MAC
0x24	Simplified GTS Specification IE	X					10.25.8.1	10.2, [B4]	MAC	MAC
0x25	LECIM Capabilities IE	X		X	X	X	10.15.2.2	11.1.3.11	UL	UL
0x26	TRLE Descriptor IE	X	X	X	X	X	10.37.5.1.1	10.37.4.2, 10.37.4.3	MAC	MAC
0x27	RCC Capabilities IE	X		X	X		10.13.3.1	10.13, [B4]	UL	UL
0x28	RCCN Descriptor IE	X					10.13.3.2	10.13, [B4]	UL, MAC	UL
0x29	Global Time IE	X					7.4.2.3		UL	UL
0x2a	Assigned to external organization [B2]									
0x2b	DA IE	X					10.24.2.1	10.24	UL	UL
0x2c	Ranging STS Seed and Data IE (RSSD IE)			X			10.29.7.1	10.29.7.1	UL	UL
0x2d–0x7d	Reserved									

Table 7-7—Element IDs for Header IEs (continued)

Element ID	Name	Enhanced Beacon	Enhanced ACK	Data	Multipurpose	MAC command	Format subclause	Use description	Used by	Created by
0x7e	Header Termination 1 IE	X	X	X	X	X	7.4.2.4	7.4.1	MAC	MAC
0x7f	Header Termination 2 IE	X	X	X	X	X	7.4.2.5	7.4.1	MAC	MAC
0x80–0xff	Reserved									

7.4.2.2 Vendor Specific Header IE

The Vendor Specific Header IE is reserved for the use of other protocols and/or data relevant only to certain implementations. The Vendor Specific Header IE Content field shall be formatted as illustrated in Figure 7-22.

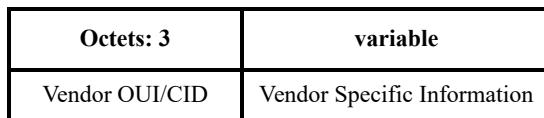


Figure 7-22—Vendor Specific Header IE Content field format

The Vendor OUI/CID field is an OUI or Company ID (CID) assigned by the IEEE Registration Authority, which shall be the sole registration authority. A value of the Vendor OUI/CID field not understood by a receiving device causes the remainder of this IE to be ignored.

The Vendor Specific Information field is defined by the vendor identified in the Vendor OUI/CID field. Its use is outside of the scope of this standard.

7.4.2.3 Global Time IE

The presence of this IE indicates that the transmitting device has a reference to global time, e.g., GPS reference time. The Global time IE Content field shall be formatted as shown in Figure 7-23.



Figure 7-23—Global Time IE Content field format

The Global Time field is an unsigned integer that contains the number of seconds elapsed since 00:00:00 UTC, January 1, 1970.

7.4.2.4 Header Termination 1 IE

The Header Termination 1 IE shall have a zero-length Content field. The use of the Header Termination 1 IE is described in 7.4.1.

7.4.2.5 Header Termination 2 IE

The Header Termination 2 IE shall have a zero-length Content field. The use of the Header Termination 2 IE is described in 7.4.1.

7.4.3 Payload IEs

7.4.3.1 General

The general format of the Payload IE is shown in Figure 7-24.

Bits: 0–10	11–14	15	Octets: 0–2047
Length	Group ID	Type = 1	Content

Figure 7-24—Format of Payload IEs

The Length field specifies the number of octets in the Content field.

The Group ID values are defined in Table 7-8 for each of the Payload IEs. In the table, an X in the column for a frame type indicates that the IE may be used in that frame. If there is not an X in the column, then the IE shall not be used in that frame. In the table, UL refers to the layers above the MAC.

Table 7-8—Payload IE Group ID

Group ID value	Name	Enhanced Beacon	Enhanced ACK	Data	Multipurpose	MAC command	Format subclause	Use description	Used by	Created by
0x0	Encapsulated Service Data Unit (ESDU) IE	X		X	X	X	7.4.3.2	7.4.3.2	UL	UL
0x1	MLME IE	X	X	X	X	X	7.4.3.3	7.4.3.3	MAC	MAC
0x2	Vendor Specific Nested IE	X	X	X	X	X	7.4.4.3	—	UL	UL
0x3–0xe	Reserved									
0xf	Payload Termination IE	X	X	X	X	X	7.4.3.4	7.4.1	MAC	MAC

7.4.3.2 Encapsulated Service Data Unit (ESDU) IE

An encapsulated service data unit (ESDU) IE encapsulates a higher layer payload that is carried in the Content field. Content is sent as received, i.e., no octet ordering changes shall be made.

7.4.3.3 MLME IE

The Content field of the MLME IE shall be formatted as illustrated in Figure 7-25.

Octets: variable	variable	...	variable
Nested IE	Nested IE	...	Nested IE

Figure 7-25—MLME IE Content field format

The Nested IEs formats are defined in 7.4.4.1.

7.4.3.4 Payload Termination IE

The Payload Termination IE shall have a zero-length Content field.

7.4.4 Nested IE

7.4.4.1 Format of Nested IE

The Nested IE of type short shall be formatted as illustrated in Figure 7-26.

Bits: 0–7	8–14	15	Octets: 0–255
Length	Sub-ID	Type = 0	Content

Figure 7-26—Nested IE of type short format

The Nested IE of type long shall be formatted as illustrated in Figure 7-27.

Bits: 0–10	11–14	15	Octets: 0–2047
Length	Sub-ID	Type = 1	Content

Figure 7-27—Nested IE of type long format

The Length field specifies the number of octets in the Content field.

The Sub-ID field values for Nested IEs of type short are defined in Table 7-9. In the table, an X in the column for a frame type indicates that the IE may be used in that frame. If there is not an X in the column, then the IE shall not be used in that frame. In the table, UL refers to the layers above the MAC.

The Sub-ID field values for Nested IEs of type long are given in Table 7-10. In the table, an X in the column for a frame type indicates that the IE may be used in that frame. If there is not an X in the column, then the IE shall not be used in that frame. In the table, UL refers to the layers above the MAC.

Table 7-9—Sub-ID allocation for short format

Sub-ID value	Name	Enhanced Beacon	Enhanced ACK	Data	Multipurpose	MAC command	Format subclause	Use description	Used by	Created by
0x00–0x0f	Reserved for type long format									
0x10–0x19	Reserved									
0x1a	TSCH Synchronization IE	X					10.3.9.1	10.3	MAC	MAC
0x1b	TSCH Slotframe and Link IE	X					10.3.9.2	10.3	UL	UL
0x1c	TSCH Timeslot IE	X					10.3.9.3	10.3	UL	MAC
0x1d	Hopping Timing IE	X					10.5.6.1	10.5	MAC	MAC
0x1e	Enhanced Beacon Filter IE					X	7.4.4.2	10.19, 10.2.4	MAC	UL
0x1f	MAC Metrics IE	X		X	X		10.27.2.1	10.27	UL	MAC
0x20	All MAC Metrics IE	X		X	X		10.27.2.2	10.27	UL	MAC
0x21	Coexistence Specification IE	X					10.9.4.1	6.4.2.2, 10.9	UL	MAC
0x22	SUN Device Capabilities IE			X	X		10.14.3.1	10.14, 11.1.3.9, 20.2.2.3, 20.3.5, 20.5, [B4]	UL, MAC	MAC
0x23	SUN FSK Generic PHY IE	X		X	X	X	10.14.3.2	10.14, 11.1.3.9, 20.3	UL, MAC	MAC
0x24	Mode Switch Parameter IE	X		X	X	X	10.14.3.3	10.14, 20.2.4, 20.5	MAC	UL
0x25	PHY Parameter Change IE	X			X		10.26.3.1	10.26	MAC	UL
0x26	O-QPSK PHY Mode IE			X	X		10.26.3.2	10.26	MAC	UL
0x27	PCA Allocation IE	X					10.10.3.1	10.10	MAC	UL
0x28	LECIM DSSS Operating Mode IE			X	X		10.15.3.1	10.26	MAC	UL
0x29	LECIM FSK Operating Mode IE			X	X		10.15.3.2	10.26	MAC	UL
0x2a	Reserved									
0x2b	TVWS PHY Operating Mode Description IE				X		10.7.3.1	10.7	MAC	UL
0x2c	TVWS Device Capabilities IE	X		X	X		10.7.3.2	10.7	UL, MAC	UL

Table 7-9—Sub-ID allocation for short format (continued)

Sub-ID value	Name	Enhanced Beacon	Enhanced ACK	Data	Multipurpose	MAC command	Format subclause	Use description	Used by	Created by
0x2d	TVWS Device Category IE	X					10.7.3.3	10.7	UL	UL
0x2e	TVWS Device Identification IE	X					10.7.3.4	10.7	UL	UL
0x2f	TVWS Device Location IE	X					10.7.3.5	10.7	UL	UL
0x30	TVWS Channel Information Query IE	X					10.7.3.6	10.7	UL	UL
0x31	TVWS Channel Information Source IE	X					10.7.3.7	10.7	UL	UL
0x32	CTM IE	X					10.7.3.8	10.7	UL	UL
0x33	Timestamp IE	X					10.7.3.9	10.7, 10.29.5	MAC	MAC
0x34	Timestamp Difference IE	X					10.7.3.10	10.7, 10.29.5	MAC	MAC
0x35	TMCTP Specification IE	X					10.8.4.1	10.8	UL	UL
0x36	RCC PHY Operating Mode IE			X	X		10.13.4.1	10.26	MAC	UL
0x37	Link Margin IE		X				10.28.6.1	10.28	UL, MAC	UL, MAC
0x38	RS-GFSK Device Capabilities IE	X	X	X	X		10.26.3.3	10.26, 32.3	UL, MAC	UL, MAC
0x39	Multi-PHY IE	X	X	X	X		10.26.3.4	10.26, 18.3	UL	UL
0x3a–0x3f	Reserved									
0x40	Vendor Specific IE	X	X	X	X	X	7.4.4.3	—	UL	UL
0x41–0x45	Reserved									
0x46	SRM IE	X			X	X	10.28.5.1	10.28	UL	UL, MAC
0x47	LECIM FSK Split Operating Mode IE			X	X		10.15.3.3	10.26, 24.2	MAC	UL
0x48	Ranging Reply Time Instantaneous IE (RRTI IE)			X			10.29.8.1	10.29.6.4, 10.29.6.7, 10.32.4, 10.32.5, 10.32.6, 10.32.7	UL	MAC
0x49	Advanced Ranging Control IE (ARC IE)			X			10.32.9.1	10.32	UL	UL

Table 7-9—Sub-ID allocation for short format (continued)

Sub-ID value	Name	Enhanced Beacon	Enhanced ACK	Data	Multipurpose	MAC command	Format subclause	Use description	Used by	Created by
0x4a	Ranging Interval Update IE (RIU IE)			X			10.32.9.2	10.32.3.2	UL	UL
0x4b	Ranging Round IE (RR IE)			X			10.32.9.3	10.32.3.3	UL	UL
0x4c	Ranging Block Update IE (RBU IE)			X			10.32.9.4	10.32.3.3	UL	UL
0x4d	Ranging Contention Phase Structure IE (RCPS IE)			X			10.32.9.5	10.32.2	UL	UL
0x4e	Ranging Contention Maximum Attempts IE (RCMA IE)			X			10.32.9.6	10.32	UL	UL
0x4f	Ranging STS Seed and Data IE (RSSD IE)			X			10.29.8.2	10.32.3.2	UL	UL
0x50	Ranging Change Request IE (RCR IE)			X			10.32.9.7	10.32.3.2	UL	UL
0x51	Ranging Device Management IE (RDM IE)			X			10.32.9.8	10.32	UL	UL
0x52	Ranging Request Measurement and Control IE (RRMC IE)			X			10.29.8.3	10.29.6.3, 10.29.6.4, 10.29.6.6, 10.29.6.7, 10.32.4, 10.32.5, 10.32.6, 10.32.7	UL	UL
0x53	Ranging Measurement Information IE (RMI IE)			X			10.29.8.4	10.29.6.3, 10.29.6.4, 10.29.6.6, 10.29.6.7, 10.32.4, 10.32.5, 10.32.6, 10.32.7	UL	UL, MAC
0x54	SP3 Ranging Request Reports IE (SRRR IE)			X			10.32.9.9	10.32.8.2, 10.32.8.3	UL	UL
0x55	Ranging Channel and Preamble Code Selection IE (RCPCS IE)			X			10.29.8.5	10.29.6.8	UL	UL
0x56	Ranging Reply Time Negotiation IE (RRTN IE)			X			10.29.8.6	10.29.6.4, 10.29.6.5	UL	UL
0x57	Ranging Message Non Receipt IE (RMNR IE)			X			10.34.2.1	10.34	UL	UL

Table 7-9—Sub-ID allocation for short format (continued)

Sub-ID value	Name	Enhanced Beacon	Enhanced ACK	Data	Multipurpose	MAC command	Format subclause	Use description	Used by	Created by
0x58	Ranging Ancillary Information Message Counter and Type IE (RAICT IE)		X			10.35.2.1	10.35	UL	UL	
0x59	Ranging Multiple Message Receipt Confirmation IE (RMMRC IE)		X			10.36.2.1	10.36	UL	UL	
0x5a	Authenticated Challenge-Response Ranging Control IE (ACRRC IE)				X	10.33.6.1	10.33.4, 10.33.5	UL, MAC	UL, MAC	
0x5b	Ranging Descriptor IE (RD IE)	X				10.30.2.1	10.36	UL	UL	
0x5c	ChallengeResponseTransf er IE			X		10.33.6.2	10.33.5.2, 10.33.5.5	UL	UL	
0x5d–0x7f	Reserved									

Table 7-10—Sub-ID allocation for long format

Sub-ID value	Name	Enhanced Beacon	Enhanced ACK	Data	Multipurpose	MAC command	Format subclause	Use description	Used by	Created by
0x0–0x7	Reserved									
0x8	Vendor Specific Nested IE	X	X	X	X	X	7.4.4.3	—	UL	UL
0x9	Channel Hopping IE	X					10.16.2.1	10.16, 10.3	MAC	MAC
0xa–0xf	Reserved									

7.4.4.2 Enhanced Beacon Filter IE

The Enhanced Beacon Filter IE Content field shall be formatted as illustrated in Figure 7-28. No more than one Enhanced Beacon Filter IE shall be conveyed per Enhanced Beacon Request frame.

Bits: 0	1	2	3–4	5–7	Octets: 0/1	0/1	0/1/2/3
Permit Joining On	Include Link Quality Filter	Include Percent Filter	Attribute IDs Length	Reserved	Link Quality	Percent Filter	Attribute IDs

Figure 7-28—Enhanced Beacon Filter IE Content field format

If the Permit Joining On field is set, only devices supporting Enhanced Beacon Request command/Enhanced Beacon frame with permit joining on shall respond to the Enhanced Beacon Request command.

The Include Link Quality Filter field shall be set to one if a Link Quality field is included and shall be set to zero otherwise.

The Link Quality filter is an unsigned integer that indicates the minimum link quality that should be met in order for a device to respond to the request.

The Include Percent filter bit shall be set to one if a Percent Filter field is included and shall be set to zero otherwise.

The Percent Filter field contains a scaled value from 0x00 to 0x64 representing zero to 100% probability for a given device to respond to the enhanced beacon request. The receiving device shall then randomly determine if it is to respond to the Enhanced Beacon Request command (if supporting Enhanced Beacon Request command/Enhanced Beacon frame) based on meeting this probability. For example, if the probability is set to 10%, then a device would respond, on average, to one out of every ten requests.

The Attribute IDs Length field is an unsigned integer that shall be set to the length in octets of the Attribute IDs field.

The Attribute IDs field is a bitmap identifying which of the Attribute Request IDs, defined in Table 6-1, are being requested. If attribute ID n is being requested, then bit n of the Attribute IDs field would be set to one. All other bits shall be set to zero.

7.4.4.3 Vendor Specific Nested IE

The Vendor Specific Nested IE is reserved for the use of other protocols and/or data relevant only to certain implementations. The Vendor Specific Nested IE Content field shall be formatted as illustrated in Figure 7-29.

Octets: 3	variable
Vendor OUI/CID	Vendor Specific Information

Figure 7-29—Vendor Specific Nested IE Content field format

The Vendor OUI/CID field is defined in 7.4.2.2. A value of the Vendor OUI/CID field not understood by a receiving device causes the remainder of this IE to be ignored.

The Vendor Specific Information field is defined by the vendor identified in the Vendor OUI/CID field. Its use is outside of the scope of this standard.

7.5 MAC commands

7.5.1 Command ID field

The MAC commands are listed in Table 7-11 along with their associated command ID. All devices shall be capable of transmitting and receiving all MAC commands with Command ID field of values 0x07–0x08. A device supporting one of timeslot relaying based link extension (TRLE), DSME, RIT, or dedicated beacon slot (DBS) options shall support the associated MAC commands as identified by the associated functional group prefix, e.g., “DSME” for the DSME option.

Table 7-11—MAC commands

Command ID	Command name	Subclause
0x01	Association Request command	10.21.5.1
0x02	Association Response command	10.21.5.2
0x03	Disassociation Notification command	10.21.5.3
0x04	Data Request command	10.22.4.1
0x05	PAN ID Conflict Notification command	10.17.4.1
0x06	Orphan Notification command	10.20.3.1
0x07	Beacon Request command	7.5.2
0x08	Coordinator Realignment command	7.5.4
0x09	GTS request command	10.25.9.1
0x0a	TRLE Management Request command	10.37.5.2.1
0x0b	TRLE Management Response command	10.37.5.2.2
0x0c–0x12	Reserved	
0x13	DSME Association Request command	10.4.12.1
0x14	DSME Association Response command	10.4.12.2
0x15	DSME GTS Request command	10.4.12.3
0x16	DSME GTS Response command	10.4.12.4
0x17	DSME GTS Notify command	10.4.12.5
0x18	DSME Information Request command	10.4.12.6
0x19	DSME Information Response command	10.4.12.7
0x1a	DSME Beacon Allocation Notification command	10.4.12.8
0x1b	DSME Beacon Collision Notification command	10.4.12.9
0x1c	DSME Link Report command	10.4.12.10
0x1d–0x1f	Reserved	
0x20	RIT Data Request command	10.6.6.1

Table 7-11—MAC commands (continued)

Command ID	Command name	Subclause
0x21	DBS Request command	10.8.5.1
0x22	DBS Response command	10.8.5.2
0x23	RIT Data Response command	10.6.6.2
0x24	Vendor Specific command	7.5.5
0x25	SRM Request command	10.28.7.1
0x26	SRM Response command	10.28.7.2
0x27	SRM Report command	10.28.7.3
0x28	SRM Information command	10.28.7.4
0x29	Ranging Verifier command	10.33.7.1
0x2a	Ranging Prover command	10.33.7.2
0x2b–0xff	Reserved	

7.5.2 Beacon Request command

The Beacon Request command has no Content field.

The Destination Addressing Mode field shall be set to indicate short addressing, and the Source Addressing Mode field shall be set to indicate that the source addressing information is not present.

The Frame Pending field shall be set to zero and ignored upon reception. The AR field and Security Enabled field shall also be set to zero.

The Destination PAN ID field shall contain the broadcast PAN ID. The Destination Address field shall contain the broadcast short address.

7.5.3 Enhanced Beacon Request command

The Enhanced Beacon Request command is a Beacon Request command with a Frame Version field set to 0b10.

The Enhanced Beacon Request command has no Content field.

The Enhanced Beacon Request command may contain an Enhanced Beacon Filter IE, as defined in 7.4.4.2, and/or a set of IE IDs. The Enhanced Beacon Filter allows a device to request Enhanced Beacon frames, as described in 10.2.4.

The Frame Pending field of the Frame Control field shall be set to zero and ignored upon reception.

The AR field shall be set to zero. If the Enhanced Beacon Request command is being sent on a particular PAN ID that is not the broadcast PAN ID, the Security Enable field may be set to one; otherwise, it shall be set to zero.

The Destination PAN ID field, if present, shall contain either a specific PAN ID or a broadcast PAN ID if *macImplicitBroadcast* is FALSE.

Frames intended for all coordinators shall set the Destination Address field to the broadcast short address. Frames intended for a specific coordinator shall set the Destination Address field to the coordinator's short address.

7.5.4 Coordinator Realignment command

The Destination Addressing Mode field shall be set to indicate extended addressing if the command is directed to an orphaned device or set to indicate short addressing if it is to be broadcast to the PAN. The Source Addressing Mode field shall be set to indicate extended addressing.

The Frame Pending field shall be set to zero and ignored upon reception.

The AR field shall be set to one if the command is directed to an orphaned device or set to zero if the command is to be broadcast to the PAN.

The Frame Version field shall be set to 0x01 if the length of the command is more than seven octets.

The Destination PAN ID field when present shall contain the broadcast PAN ID. The Destination Address field shall contain the extended address of the orphaned device if the command is directed to an orphaned device. Otherwise, the Destination Address field shall contain the broadcast short address. The Source PAN ID field shall contain the value of *macPanId*, and the Source Address field shall contain the value of *macExtendedAddress*.

The Coordinator Realignment command Content field shall be formatted as illustrated in Figure 7-30.

Octets: 2	2	1	2	Bits: 0–6	7
PAN ID	Coordinator Short Address	Channel Number	Short Address	Reserved/Channel Number	Extended Channel Number

Figure 7-30—Coordinator Realignment command Content field format

The PAN ID field shall contain the PAN ID that the coordinator intends to use for all future communications.

The Coordinator Short Address field shall contain the value of *macShortAddress*.

The Reserved/Channel Number field and Extended Channel Number field may be omitted from the Coordinator Realignment command. The Length field of the Coordinator Realignment command is used to determine if these fields are present.

The Extended Channel Number field indicates the contents of the Reserved/Channel Number field. If the Extended Channel Number field is set to zero, the Reserved/Channel Number field is reserved.

If the Extended Channel Number field is set to one, the Reserved/Channel Number field shall be used for the most significant bits of the channel number, and the Channel Number field shall contain the least significant bits of the channel number.

For example, in the case that the Reserved/Channel Number field contains 0x9e and the Channel Number field contains 0xad, then Extended Channel Number field is set to one, then the channel number is 0x1ead.

If the Coordinator Realignment command is broadcast to the PAN, the Short Address field shall be set to 0xffff and ignored on reception. If the Coordinator Realignment command is sent directly to an orphaned device, the Short Address field shall contain the short address that the orphaned device shall use to operate on the PAN. If the orphaned device does not have a short address, because it always uses its extended address, this field shall contain the value 0xfffe.

7.5.5 Vendor Specific command

The Vendor Specific command is reserved for the use of other protocols and/or data relevant only to certain implementations. The Vendor Specific command Content field shall be formatted as illustrated in Figure 7-31.

Octets: 3	variable
Vendor OUI/CID	Vendor Specific Information

Figure 7-31—Vendor Specific command Content field format

The Vendor OUI/CID field is defined in 7.4.2.2. A value of the Vendor OUI/CID field not understood by a receiving device causes the command to be ignored.

The Vendor Specific Information field is defined by the vendor identified in the Vendor OUI/CID field. Its use is outside of the scope of this standard.

8. MAC services

8.1 Overview

The MAC sublayer provides an interface between the next higher layer and the PHY. The MAC sublayer conceptually includes a management entity called the MLME. This entity provides the service interfaces through which layer management is invoked. The MLME is also responsible for maintaining a database of managed objects pertaining to the MAC sublayer. This database is referred to as the MAC sublayer PIB.

Figure 8-1 depicts the components and interfaces of the MAC sublayer.

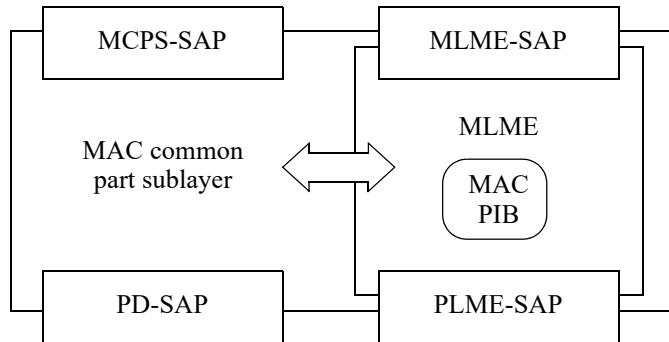


Figure 8-1—MAC sublayer reference model

The MAC sublayer provides two services, accessed through two SAPs:

- The MAC data service, accessed through the MCPS data SAP (MCPS-SAP)
- The MAC management service, accessed through the MLME-SAP

These two services provide the interface between the next higher layer and the PHY. In addition to these external interfaces, an implicit interface also exists between the MLME and the MCPS that allows the MLME to use the MAC data service.

8.2 MAC management service

8.2.1 Primitives supported by the MLME-SAP interface

The MLME-SAP allows the transport of management commands between the next higher layer and the MLME. Table 8-1 summarizes the primitives supported by the MLME through the MLME-SAP interface. Primitives marked with an asterisk (*) are optional.

Table 8-1—Summary of the primitives accessed through the MLME-SAP

Name	Request	Indication	Response	Confirm
MLME-ASSOCIATE	10.21.6.1.2*	10.21.6.1.3*	10.21.6.1.4*	10.21.6.1.5*
MLME-BEACON-NOTIFY		8.2.4.3*		
MLME-BEACON	8.2.10.1	8.2.10.3		8.2.10.2
MLME-BEACON-REQUEST		8.2.10.4		

Table 8-1—Summary of the primitives accessed through the MLME-SAP (continued)

Name	Request	Indication	Response	Confirm
MLME-CALIBRATE	10.29.9.3.2*			10.29.9.3.3*
MLME-COMM-STATUS		8.2.4.4		
MLME-DBS	10.8.6.1*	10.8.6.2*	10.8.6.3*	10.8.6.4*
MLME-DA	10.24.3.1*	10.24.3.2*		10.24.3.3*
MLME-DISASSOCIATE	10.21.6.2.2*	10.21.6.2.3*		10.21.6.1.5*
MLME-DPS	10.29.9.1.2*	10.29.9.1.4*		10.29.9.1.3*
MLME-GET	8.2.5.2			8.2.5.3
MLME-GTS	10.25.10.2*	10.25.10.4*		10.25.10.3*
MLME-IE-NOTIFY		8.2.4.5*		
MLME-ORPHAN		10.20.4.2*	10.20.4.3*	
MLME-PHY-DETECT		8.2.4.6*		
MLME-PHY-OP-SWITCH	10.26.4.2*	10.26.4.3*		10.26.4.4*
MLME-POLL	10.22.5.2*			10.22.5.3*
MLME-RESET	8.2.6.2			8.2.6.3
MLME-RIT-REQ		10.6.7.1*		
MLME-RIT-RES	10.6.7.2*	10.6.7.3*		10.6.7.4*
MLME-RX-ENABLE	8.2.7.3*	8.2.7.5*		8.2.7.4*
MLME-SCAN	8.2.8.2*			8.2.8.3*
MLME-SET	8.2.5.4			8.2.5.5
MLME-START	8.2.9.2			8.2.9.3
MLME-START-SUPERFRAME	10.2.9.2*			10.2.9.3*
MLME-STS	10.29.9.4.1*			10.29.9.4.2*
MLME-SYNC	10.2.10.2*			
MLME-SYNC-LOSS		10.2.10.3*		
MLME-SOUNDING	10.29.9.2.2*			10.29.9.2.3*
MLME-SRM-REPORT	10.28.8.2.1*	10.28.8.2.2*		10.28.8.2.3*
MLME-SRM-INFORMATION	10.28.8.3.1*	10.28.8.3.2*		10.28.8.3.3*
MLME-SRM-REQ	10.28.8.4.1*	10.28.8.4.2*		10.28.8.4.3*
MLME-SRM-RES	10.28.8.5.1*	10.28.8.5.2*		10.28.8.5.3*

8.2.2 Common requirements for MLME primitives

If any error occurs during the outgoing frame security procedure, as described in 9.2.2, for a request primitive, the MLME will discard the frame and issue the corresponding confirm primitive with the error returned by the outgoing frame security procedure.

If any error occurs during the outgoing frame security procedure, as described in 9.2.2, for a response primitive, the MLME will discard the frame and issue the MLME-COMM-STATUS.indication primitive with the error returned by the outgoing frame security procedure.

The list of generic security errors is given below, and any MLME or MCSP confirm primitive may return them inside the Status parameter even when these errors are not listed in the Valid range column of the Status parameter.

- COUNTER_ERROR: Returned when sending frame, if the frame counter has maximum value. Also returned when receiving a frame where the frame counter is smaller than that received previously.
- IMPROPER_IE_SECURITY: One of the IEs in the frame failed security processing.
- IMPROPER_KEY_TYPE: Returned when the incoming security policy checking notices that key used to protect the frame was not the one that was configured in the security policy.
- IMPROPER_SECURITY_LEVEL: Returned when the incoming security policy checking noticed that security level of the incoming frame is not allowed by security policy.
- KEY_LENGTH_MISMATCH: Returned when the *secKey* within the *secKeyDescriptor* has a length that is inconsistent with the *secAeadAlgorithm*.
- SECURITY_ERROR: Returned when unsecuring of the frame fails in the incoming security process, for example because the message integrity code (MIC) is incorrect.
- UNAVAILABLE_DEVICE: Returned when incoming security process cannot find the device indicated in the frame.
- UNAVAILABLE_KEY: Returned when outgoing security process cannot find key requested by the MLME primitive, or when the incoming security process cannot find key indicated in the frame.
- UNAVAILABLE_SECURITY_LEVEL: Returned when incoming security process cannot find the matching *secSecurityLevelDescriptor* for the incoming frame.
- UNSUPPORTED_ALGORITHM: Returned when the *secAeadAlgorithm* within the *secKeyDescriptor* is not supported.
- UNSUPPORTED_LEGACY: Returned when secured frame is received with Frame Version field set to zero.
- UNSUPPORTED_SECURITY: Returned when security is requested for outgoing frame, or when secured frame is received and the security is not enabled in the device. Also received if the Auxiliary Security Header has security level of zero in it.

If any parameter in the request primitive is not supported or is out of range, the MAC sublayer will issue the corresponding confirm primitive with a Status of INVALID_PARAMETER.

If any parameter in the response primitive is not supported or is out of range, the MAC sublayer will issue the MLME-COMM-STATUS.indication primitive with a Status of INVALID_PARAMETER.

If the MLME is unable to send the frame required by a request primitive due to a CSMA-CA algorithm failure, the MLME will issue the corresponding confirm primitive with a Status parameter value of CHANNEL_ACCESS_FAILURE.

If the MLME successfully transmits the frame required by a request primitive, but the expected acknowledgment is not received, the MLME will issue the corresponding confirm primitive with a Status parameter value of NO_ACK.

The list of generic errors is given below, and any MLME or MCSP confirm primitive may return them inside the Status parameter even when these errors are not listed in the Valid range column of the Status parameter.

- CHANNEL_ACCESS_FAILURE: CSMA-CA algorithm fails.
- FRAME_TOO_LONG: The length of the frame exceeds the maximum size it can be. This might be because the frame was expanded because IEs were added, or because of security processing. It is also returned if requested transaction is too large to fit in the CAP or GTS.
- INVALID_PARAMETER: Some of the parameters are not supported or are out of range.
- NO_ACK: No acknowledgment is received when it is expected.
- TRANSACTION_EXPIRED: Returned when response is expected but it was not received within the expected time, or when the critical transaction is not sent out in time.
- TRANSACTION_OVERFLOW: Returned when there is no capacity to store another transaction.

8.2.3 SecurityParameterDescriptor

Several MLME primitives and PIB attributes include security parameters. These parameters include security level, key id mode, key source, and key index. Instead of passing each of those parameters separately, MLME primitives instead use SecurityParameterDescriptor object specified in Table 8-2.

Table 8-2—Elements of SecurityParameterDescriptor

Name	Type	Valid range	Description
SecurityLevel	Integer	0x00–0x07	The security level purportedly used by the received frame or to be used when transmitting a frame, as defined in Table 9-6.
KeyIdMode	Integer	0x00–0x03	The mode used to identify the key purportedly used by the originator of the received frame or to be used when transmitting a frame, as defined in Table 9-7. This parameter is ignored if the SecurityLevel parameter is set to 0x00.
KeySource	Set of octets	As specified by the KeyIdMode parameter	The originator of the key purportedly used by the originator of the received frame or to be used when transmitting a frame, as described in 9.4.4.2. This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00 or 0x01.
KeyIndex	Integer	0x01–0xff	The index of the key purportedly used by the originator of the received frame or to be used when transmitting a frame, as described in 9.4.4.3. This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00.

8.2.4 Communications notification primitives

8.2.4.1 General

The MLME-SAP beacon primitives define how a coordinator in a PAN not using periodic beacons sends a beacon or an enhanced beacon, or respond to beacon/enhanced beacon requests, and notifies the upper layer of beacon reception. Coordinators operating in a beacons PAN use MLME-START to configure beacons and enhanced beacons.

The MLME-BEACON-NOTIFY.indication primitive is used to notify the next higher layer when a beacon or enhanced beacon is received during normal operating conditions. The MLME-COMM-STATUS.indication primitive is used to notify the next higher layer that an error has occurred during the

processing of a frame that was instigated by a response primitive. The MLME-PHY-DETECT.indication primitive is used to notify the next higher layer that the 250 kb/s O-QPSK PHY has been detected during operation of the 2000 kb/s, 2450 MHz MSK PHY.

8.2.4.2 PanDescriptor

Several MLME primitives include structure containing information about the PANs. The elements of the PanDescriptor structure are defined in Table 8-3.

Table 8-3—Elements of PanDescriptor

Name	Type	Valid range	Description
CoordAddrMode	Enumeration	SHORT, EXTENDED	The coordinator addressing mode corresponding to the received beacon frame.
CoordPanId	Integer	0x0000–0xffff	The PAN ID of the coordinator as specified in the received beacon frame.
CoordAddress	Short address or extended address	As specified by the CoordAddrMode parameter	The address of the coordinator as specified in the received beacon frame.
ChannelInfo	Channel information structure as defined in 11.1.3.1	Any valid channel	The current channel occupied by the network.
BeaconType	Enumeration	BEACON, ENHANCED_BEACON	Indicates a beacon or enhanced beacon was received.
HeaderIeList	Set of header IEs as described in 7.4.2	—	The header IEs, excluding Termination IEs, that were included in the Beacon frame. If empty, then no header IEs were included.
PayloadIeList	Set of payload IEs as described in 7.4.3	—	The payload IEs, excluding Termination IEs, that were included in the Beacon frame. If empty, then no payload IEs were included.
BeaconPayload	Set of octets	—	The set of octets comprising the Beacon Payload field, if present.
SuperframeSpec	Bitmap	As defined in 7.3.1	The superframe specification as specified in the received beacon frame.
GtsPermit	Boolean	TRUE, FALSE	TRUE if the beacon is from the PAN coordinator that is accepting GTS requests.
AddrList	List of addresses	—	The addresses of the devices for which the beacon source has data. This list contains both short and extended addresses pending.
LinkQuality	Integer	0x00–0xff	The LQI at which the network beacon was received. Lower values represent lower LQI, as defined in 11.2.7.
TimeStamp	Integer	0x000000–0xffffffff	The time at which the Beacon frame was received. The format of timestamp is specified in 6.5.3.

Table 8-3—Elements of PanDescriptor (continued)

Name	Type	Valid range	Description
SecurityStatus	Enumeration	SUCCESS, also see 8.2.2	SUCCESS if there was no error in the security processing of the frame. One of the other Status codes indicating an error in the security processing otherwise, as described in 9.2.4.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.
CodeList	Set of integers	—	The HRP UWB preamble codes, as described in 16.2.6.2, or CSS subchirp codes, as described in 15.3, in use when the channel was detected. For all other PHY types, this is empty.

8.2.4.3 MLME-BEACON-NOTIFY.indication

The MLME-BEACON-NOTIFY.indication primitive is used to send parameters contained within a Beacon frame or an Enhanced Beacon frame received by the MAC sublayer to the next higher layer when either *macAutoRequest* is set to FALSE or when the Beacon frame contains one or more octets of payload. The primitive also sends a measure of the LQI and the time the Beacon frame was received.

If Beacon frame or an Enhanced Beacon frame is received and *macNotifyAllBeacons* is TRUE, then the MLME shall indicate the beacon parameters to the next higher layer by issuing the MLME-BEACON-NOTIFY.indication primitive.

The semantics of this primitive are as follows:

```
MLME-BEACON-NOTIFY.indication ( 
    Sn,
    PanDescriptor
)
```

The primitive parameters are defined in Table 8-4.

Table 8-4—MLME-BEACON-NOTIFY.indication parameters

Name	Type	Valid range	Description
Sn	Integer	0x00–0xff	The BSN or EBSN of the Beacon frame.
PanDescriptor	PanDescriptor value	As defined in Table 8-3	The PanDescriptor for the received Beacon frame.

8.2.4.4 MLME-COMM-STATUS.indication

The MLME-COMM-STATUS.indication primitive allows the MLME to indicate a communications status.

The semantics of this primitive are as follows:

```
MLME-COMM-STATUS.indication ( 
    PanId,
    SrcAddrMode,
    SrcAddr,
    DstAddrMode,
    DstAddr,
    SecurityParams,
    Msdu,
    HeaderIeList,
    PayloadIeList,
    IeStatusList,
    Status
)
```

The primitive parameters are defined in Table 8-5.

Table 8-5—MLME-COMM-STATUS.indication parameters

Name	Type	Valid range	Description
PanId	Integer	0x0000–0xffff	The PAN ID of the device from which the frame was received or to which the frame was being sent.
SrcAddrMode	Enumeration	NONE, SHORT, EXTENDED	The source addressing mode for this primitive.
SrcAddr	—	As specified by the SrcAddrMode parameter	The address of the entity from which the frame causing the error originated.
DstAddrMode	Enumeration	NONE, SHORT, EXTENDED	The destination addressing mode for this primitive.
DstAddr	—	As specified by the DstAddrMode parameter	The address of the device for which the frame was intended.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.
Msdu	Set of octets	—	The set of octets forming the MSDU being indicated by the MAC sublayer entity including payload IEs, if present.
HeaderIeList	Set of header IEs as described in 7.4.2	—	The header IEs, excluding Termination IEs, that were included in the MAC frame. If empty, then no header IEs were in the MAC frame.
PayloadIeList	Set of payload IEs as described in 7.4.3	—	The payload IEs, excluding Termination IEs, that were included in the MAC frame. If empty, then no payload IEs were in the MAC frame.
IeStatusList	List of Status for each IE	PASSED or FAILED for each IE in frame	Status of each IE in the frame telling whether they passed or failed the security policy checks as defined in 9.2.8 and 9.2.9.
Status	Enumeration	SUCCESS, see also 8.2.2	The communications status.

The MLME-COMM-STATUS.indication primitive is generated by the MLME and issued to its next higher layer either following a transmission instigated through a response primitive or on receipt of a frame that generates an error in its security processing, as described in 9.2.4. If the request to transmit was successful, the Status parameter shall be set to SUCCESS.

NOTE—If Status is IMPROPER_IE_SECURITY then the IEs that passed security processing are delivered to the upper layer, and/or are processed by the MAC. All IEs are delivered by MLME-COMM-STATUS.indication to the upper layer, including those that failed security processing.

8.2.4.5 MLME-IE-NOTIFY.indication

The MLME-IE-NOTIFY.indication primitive is used to send IEs contained in a MAC Command frame, Multipurpose frame, or an Enh-Ack frame.

The semantics of this primitive are as follows:

```
MLME-IE-NOTIFY.indication ( SrcAddrMode,
                            SrcPanId,
                            SrcAddr,
                            DstAddrMode,
                            DstPanId,
                            DstAddr,
                            FrameType,
                            CommandIdentifier,
                            HeaderIEList,
                            PayloadIEList,
                            SecurityParams )
```

The primitive parameters are defined in Table 8-6.

Table 8-6—MLME-IE-NOTIFY.indication parameters

Name	Type	Valid range	Description
SrcAddrMode	Enumeration	NONE, SHORT, EXTENDED	The source addressing mode of the source of the frame that was received.
SrcPanId	Integer	0x0000–0xffff	The PAN ID of the source of the frame that was received. Valid only when a source PAN ID is included in the received frame.
SrcAddr	—	As specified by the SrcAddrMode parameter	The source address of the frame that was received. Valid only when the source address is included in the received frame.
DstAddrMode	Enumeration	NONE, SHORT, EXTENDED	The destination addressing mode of the source of the frame that was received.
DstPanId	Integer	0x0000–0xffff	The PAN ID of the destination of the frame that was received. Valid only when a destination PAN ID is included in the received frame.

Table 8-6—MLME-IE-NOTIFY.indication parameters (continued)

Name	Type	Valid range	Description
DstAddr	—	As specified by the DstAddrMode parameter	The destination address of the frame that was received. Valid only when the destination address is included in the received frame.
FrameType	Enumeration	MAC_COMMAND, ENH_ACK, MULTIPURPOSE	The type of frame in which the IEs were received.
CommandIdentifier	Integer	As defined in Table 7-11	If the frame is a MAC Command, the command type of the frame, otherwise empty.
HeaderIeList	Set of header IEs as described in 7.4.2	—	The header IEs, excluding Termination IEs, that were included in the frame. If empty, then no header IEs were included.
PayloadIeList	Set of payload IEs as described in 7.4.3	—	The payload IEs, excluding Termination IEs, that were included in the frame. If empty, then no payload IEs were included.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

8.2.4.6 MLME-PHY-DETECT.indication

The MLME-PHY-DETECT.indication primitive is used to inform the next higher layer that the 250 kb/s O-QPSK PHY has been detected.

The semantics of this primitive are as follows:

```
MLME-PHY-DETECT.indication      ( 
                                CurrentPHY
                                )
```

The primitive parameter is defined in Table 8-7.

Table 8-7—MLME-PHY-DETECT.indication parameters

Name	Type	Valid range	Description
CurrentPHY	Enumeration	MSK_PHY_2000	PHY used when 250 kb/s O-QPSK PHY is detected.

8.2.5 Primitives for reading and writing PIB attributes

8.2.5.1 General

These primitives are used to read values from the PIB and write values to the PIB.

8.2.5.2 MLME-GET.request

The MLME-GET.request primitive requests information about a given PIB attribute.

The semantics of this primitive are as follows:

```
MLME-GET.request          (
    PibAttribute
)
```

The primitive parameters are defined in Table 8-8.

Table 8-8—MLME-GET.request parameters

Name	Type	Valid range	Description
PibAttribute	Octet string	Any of the PIB attributes defined in 8.4.3 and those in Table 9-8, or tables in 12.3.	The name of the PIB attribute to read.

On receipt of the MLME-GET.request primitive, the MLME checks to see whether the PIB attribute is a MAC PIB attribute or PHY PIB attribute. If the requested attribute is a MAC attribute, the MLME attempts to retrieve the requested MAC PIB attribute from its database. If the requested attribute is a PHY PIB attribute, the MLME attempts to retrieve the value from the PHY.

The MAC PIB contains some hierarchical data structures (for example, the TSCH *macLinkTable* or security MAC PIBs described in 9.5), and the PibAttribute parameter needs to be able to address them, i.e., it needs to be possible to get *macNodeAddress* (Table 10-18) from *macLinkTable* that matches a given *macLinkHandle*. The format for how PIB attribute is defined is outside the scope of this standard.

8.2.5.3 MLME-GET.confirm

The MLME-GET.confirm primitive reports the results of an information request from the PIB.

The semantics of this primitive are as follows:

```
MLME-GET.confirm          (
    PibAttribute,
    PibAttributeValue,
    Status
)
```

The primitive parameters are defined in Table 8-9.

Table 8-9—MLME-GET.confirm parameters

Name	Type	Valid range	Description
PibAttribute	Octet string	Any of the PIB attributes defined in 8.4.3 and those in Table 9-8 or tables in 12.3.	The name of the PIB attribute that was read.
PibAttributeValue	Various	Attribute specific, as defined in Table 8-36, Table 9-8, or tables in 12.3.	The value of the indicated PIB attribute that was read.
Status	Enumeration	SUCCESS, UNSUPPORTED_ATTRIBUTE.	The result of the request for PIB attribute information.

If the request to read a PIB attribute was successful, the primitive returns with a Status of SUCCESS. If the identifier of the PIB attribute is not found, the primitive returns with a Status of UNSUPPORTED_ATTRIBUTE. When an error code of UNSUPPORTED_ATTRIBUTE is returned, the PibAttributeValue parameter is invalid.

As MAC PIB contains some hierarchical data structures, it is also possible to provide interface where MLME-GET.confirm returns more complicated structure (for example, whole *macLinkTable* matching given *macLinkHandle*).

8.2.5.4 MLME-SET.request

The MLME-SET.request primitive attempts to write the given value to the indicated PIB attribute.

The semantics of this primitive are as follows:

```
MLME-SET.request      (
    PibAttribute,
    PibAttributeValue
)
```

The primitive parameters are defined in Table 8-10.

Table 8-10—MLME-SET.request parameters

Name	Type	Valid range	Description
PibAttribute	Octet string	As defined in Table 8-36, Table 9-8, or tables in 12.3.	The name of the PIB attribute to write.
PibAttributeValue	Various	Attribute specific; as defined in Table 8-36, Table 9-8, or tables in 12.3.	The value to write to the indicated PIB attribute.

On receipt of the MLME-SET.request primitive, the MLME checks to see whether the PIB attribute is a MAC PIB attribute or a PHY PIB attribute. If the requested attribute is a MAC attribute, the MLME attempts to write the given value to the indicated MAC PIB attribute. If the requested attribute is a PHY attribute, the MLME attempts to write the given value to the indicated PHY PIB attribute.

The MAC PIB contains some hierarchical data structures (for example, the TSCH *macLinkTable* or security MAC PIBs described in 9.5), and the PibAttribute parameter needs to be able to address them. In some cases, it will be required to remove or add elements to hierarchical tables, but the interface required is outside the scope of this standard.

For example, it needs to be possible to set *secExempt* (Table 9-15) of *secDeviceDescriptor* that matches a given *secExtAddress* inside the *secDeviceList* (Table 9-8).

NOTE—It is not possible to fetch the whole *secDeviceDescriptor* and modify it and set it back, because there are read-only fields inside the *secDeviceDescriptor* (*secDeviceMinFrameCounter*).

8.2.5.5 MLME-SET.confirm

The MLME-SET.confirm primitive reports the results of an attempt to write a value to a PIB attribute.

The semantics of this primitive are as follows:

```
MLME-SET.confirm      (
    PibAttribute,
    Status
)
```

The primitive parameters are defined in Table 8-11.

Table 8-11—MLME-SET.confirm parameters

Name	Type	Valid range	Description
PibAttribute	Octet string	As defined in Table 8-36, Table 9-8, or tables in 12.3	The name of the PIB attribute that was written.
Status	Enumeration	SUCCESS, READ_ONLY, UNSUPPORTED_ATTRIBUTE, INVALID_INDEX, INVALID_PARAMETER	The result of the request to write the PIB attribute.

The MLME-SET.confirm primitive is generated by the MLME and issued to its next higher layer in response to an MLME-SET.request primitive. The MLME-SET.confirm primitive returns a Status of either SUCCESS, indicating that the requested value was written to the indicated PIB attribute or with the Status parameter set as follows:

- READ_ONLY: The PibAttribute parameter specifies an attribute that is a read-only attribute.
- UNSUPPORTED_ATTRIBUTE: The PibAttribute parameter specifies an attribute that was not found in the database.
- INVALID_INDEX: The index inside the hierarchical values in PibAttribute is out of range.
- INVALID_PARAMETER: The PibAttributeValue parameter specifies a value that is out of the valid range for the given attribute.

If the PibAttribute parameter indicates that *macBeaconPayload* is to be set and the length of the resulting beacon frame exceeds *phyMaxPacketSize* (e.g., due to the additional overhead required for security processing), the MAC sublayer shall not update *macBeaconPayload* and will issue the MLME-SET.confirm primitive with a Status of INVALID_PARAMETER.

8.2.6 Primitives for resetting the MAC sublayer

8.2.6.1 General

These primitives are used to reset the MAC sublayer.

8.2.6.2 MLME-RESET.request

The MLME-RESET.request primitive is used by the next higher layer to request that the MLME performs a reset operation.

The semantics of this primitive are as follows:

```
MLME-RESET.request      (
    SetDefaultPib
)
```

The primitive parameters are defined in Table 8-12.

Table 8-12—MLME-RESET.request parameter

Name	Type	Valid range	Description
SetDefaultPib	Boolean	TRUE, FALSE	If TRUE, the MAC sublayer is reset, and all MAC PIB attributes are set to their default values. If FALSE, the MAC sublayer is reset, but all MAC PIB attributes retain their values prior to the generation of the MLME-RESET.request primitive.

On receipt of the MLME-RESET.request primitive, the MLME resets the PHY in an implementation-dependent manner.

8.2.6.3 MLME-RESET.confirm

The MLME-RESET.confirm primitive reports the results of the reset operation.

The semantics of this primitive are as follows:

```
MLME-RESET.confirm      (
    Status
)
```

The primitive parameter is defined in Table 8-13.

Table 8-13—MLME-RESET.confirm parameter

Name	Type	Valid range	Description
Status	Enumeration	SUCCESS	The result of the reset operation.

The Status parameter is set to SUCCESS on completion of the reset procedure.

8.2.7 Primitives for specifying the receiver enable time

8.2.7.1 General

These primitives are used to enable or disable a device's receiver at a given time.

8.2.7.2 RxInstanceDescriptor

RxInstanceDescriptor structure describes one instance of enabling receiver.

The elements of the RxInstanceDescriptor are described in Table 8-14.

Table 8-14—Elements of the RxInstanceDescriptor

Name	Type	Valid range	Description
RxOnTime	Integer	0x000000–0xffffffff	<p>Specifies the time when the receiver is enabled. In a PAN using superframe structure this parameter is specified as the number of symbols measured from the start of the superframe. If the issuing device is the PAN coordinator, the term <i>superframe</i> refers to its own superframe. Otherwise, the term refers to the superframe of the coordinator through which the issuing device is associated.</p> <p>For ERDEV, this parameter is specified in RSTUs, as defined in 10.29.1.5.</p> <p>For PANs not using superframe structure this is specified as timestamp symbols as defined in 6.5.3.</p> <p>For PANs not using superframe structure, if the RxOnTime is 0x000000 then the receiver is enabled immediately.</p>
RxOnDuration	Integer	0x000000–0xffffffff	<p>For non-ERDEV, this parameter specifies the number of symbols for which the receiver is to be enabled.</p> <p>For ERDEV, this parameter is specified in RSTUs, as defined in 10.29.1.5.</p> <p>If this parameter is equal to 0x000000, the receiver is to be disabled.</p> <p>If this parameter is equal to 0xffffffff, the receiver is to be enabled indefinitely.</p>
RxAutoOff	Boolean	TRUE, FALSE	When the RxAutoOff element is TRUE, the receiver is disabled immediately after the reception of a packet, otherwise it remains enabled for the specified RxOnDuration even after the reception.

8.2.7.3 MLME-RX-ENABLE.request

The MLME-RX-ENABLE.request primitive allows the next higher layer to request that the receiver is either enabled for a finite period of time or disabled.

The semantics of this primitive are as follows:

```
MLME-RX-ENABLE.request      (
    DeferPermit,
    RxOnInstanceList,
    RangingControl
)
```

The primitive parameters are defined in Table 8-15.

The MLME-RX-ENABLE.request primitive is generated by the next higher layer and issued to the MLME to enable the receiver for a fixed duration, at a time relative to the start of the current or next superframe on a PAN using superframe structure or at given time on a PAN not using superframe structure. For the enhanced ranging capable device (ERDEV) the time is specified in ranging scheduling time units (RSTU). For other PANs not using superframe structure the time is specified in symbols. This primitive is also generated to cancel a previously generated request to enable the receiver.

Table 8-15—MLME-RX-ENABLE.request parameters

Name	Type	Valid range	Description
DeferPermit	Boolean	TRUE, FALSE	For PANs using superframe structure, if this is TRUE then the requested operation can be deferred until the next superframe if the requested time has already passed, and if this is FALSE then the requested operation is only to be attempted in the current superframe. If the issuing device is the PAN coordinator, the term <i>superframe</i> refers to its own superframe. Otherwise, the term refers to the superframe of the coordinator through which the issuing device is associated. In other cases, the value TRUE indicates that the requested operation can be deferred for more than half a period of the time counter used, and FALSE indicates that the requested operation is only to be attempted within the current half period of the counter.
RxOnInstanceList	List of RxInstanceDescriptor	As defined in Table 8-14	List of instances when the receiver is enabled. The maximum size of the list is implementation specific and may be only one.
RangingControl	Enumeration	RANGING_OFF, RANGING_ON	A value of RANGING_OFF disables ranging and a value of RANGING_ON enables ranging.

For PANs not using the superframe structure the next higher layer use the TimeStamp parameters of MCPS-DATA.indication, MCPS-DATA.confirm, and MLME-BEACON-NOTIFY.indication as the reference to specify the RxOnTime, except when using RxOnTime value of 0x000000 which is treated as special value meaning enable or disable the receiver immediately.

The receiver is enabled or disabled exactly once per each RxInstanceList item, and the receiver will be re-enabled at the specified time for the specified duration as modified by the RxAutoOff value until the list is exhausted. The RxOnTimes in the RxInstanceList shall be in the chronological order of the required receiver enable times.

The MLME will treat a request to enable or disable the receiver as secondary to other responsibilities of the device (e.g., GTSs, coordinator beacon tracking, or beacon transmissions). When the primitive is issued to enable the receiver, the device will enable its receiver until either the device has a conflicting responsibility, the time specified by RxOnDuration has expired, or the RxAutoOff parameter is true and a packet is received. In the case of a conflicting responsibility, the device will interrupt the receive operation. After the completion of the interrupting operation, the RxOnDuration will be checked to determine whether the time has expired. If so, the operation is complete. If not, the receiver is re-enabled until either the device has another conflicting responsibility, the time specified by RxOnDuration has expired, or the RxAutoOff parameter is true and a packet is received. When the primitive is issued to disable the receiver, the device will disable its receiver unless the device has a conflicting responsibility.

Invoking a new MLME-RX-ENABLE.request while the previous list has not yet been completed, will cancel outstanding receiver enables, and perform the receiver enables and disables specified in the list specified by the new MLME-RX-ENABLE.request.

For PANs not using superframe structure, when an MLME-RX-ENABLE.request primitive is issued specifying an initial RxOnTime with a value that is more than half a period in the future, the MAC shall consider this to be a late invocation and return a status value of PAST_TIME in the

MLME-RX-ENABLE.confirm primitive, unless the DeferPermit parameter is TRUE, in which case the MLME will wait until the counter reaches the specified RxOnTime value to enable the receiver.

For PANs using superframe structure the MLME first determines whether $(\text{RxOnTime} + \text{RxOnDuration})$ is less than the beacon interval, as defined by *macBeaconOrder*. If $(\text{RxOnTime} + \text{RxOnDuration})$ is not less than the beacon interval, the MLME issues the MLME-RX-ENABLE.confirm primitive with a Status of ON_TIME_TOO_LONG.

For PANs using superframe structure the MLME then determines whether the receiver can be enabled in the current superframe. If the current time measured from the start of the superframe is less than $(\text{RxOnTime} - \text{macSifsPeriod})$, the MLME attempts to enable the receiver in the current superframe. If the current time measured from the start of the superframe is greater than or equal to $(\text{RxOnTime} - \text{macSifsPeriod})$ and DeferPermit is equal to TRUE, the MLME defers until the next superframe and attempts to enable the receiver in that superframe. Otherwise, if the MLME cannot enable the receiver in the current superframe and is not permitted to defer the receive operation until the next superframe, the MLME issues the MLME-RX-ENABLE.confirm primitive with a Status of PAST_TIME.

8.2.7.4 MLME-RX-ENABLE.confirm

The MLME-RX-ENABLE.confirm primitive reports the results of the attempt to enable or disable the receiver.

The semantics of this primitive are as follows:

```
MLME-RX-ENABLE.confirm      (
    StatusDetail,
    Status
)
```

The primitive parameters are defined in Table 8-16.

Table 8-16—MLME-RX-ENABLE.confirm parameter

Name	Type	Valid range	Description
StatusDetail	List of Enumerations	SUCCESS, PAST_TIME, ON_TIME_TOO_LONG	This parameter provides a list of result values corresponding with the items in RxInstanceList parameter passed into the MLME-RX-ENABLE.request primitive.
Status	Enumeration	SUCCESS, PAST_TIME, ON_TIME_TOO_LONG, RANGING_NOT_SUPPORTED, also see 8.2.2	The result of the request to enable or disable the receiver.

The MLME-RX-ENABLE.confirm primitive is generated by the MLME and issued to its next higher layer in response to an MLME-RX-ENABLE.request primitive. This primitive returns a Status of either SUCCESS, if the request to enable or disable the receiver was successful, or the appropriate error code.

The StatusDetail parameter is a list that may be provided in the case of a failure, to give additional information, with a status detail value for each RxInstanceList parameter item passed into the MLME-RX-ENABLE.request primitive.

A Status value of RANGING_NOT_SUPPORTED is returned if an MLME-RX-ENABLE.request primitive is issued with a RangingControl parameter value of RANGING_ON to a non-RDEV.

The other Status values are fully described in 8.2.7.3.

8.2.7.5 MLME-RX-ENABLE.indication

The MLME-RX-ENABLE.indication primitive reports when the receiver is turned off at the end of a specified RxOnDuration period.

The semantics of this primitive are as follows:

```
MLME-RX-ENABLE.indication ( 
    TimeStamp
)
```

The primitive parameters are defined in Table 8-17.

Table 8-17—MLME-RX-ENABLE.indication parameters

Name	Type	Valid range	Description
TimeStamp	Integer	0x000000–0xffffffff	Reports the time at which the receiver disable occurred. The format of timestamp is specified in 6.5.3.

The MLME-RX-ENABLE.indication primitive is issued by the MLME when the receiver is disabled at the end of the period specified by the RxOnDuration parameter of the MLME-RX-ENABLE.request primitive. When the RxInstanceList parameter contains multiple items, a separate MLME-RX-ENABLE.indication is issued with respect to each separate disable.

When the RxAutoOff parameter is TRUE for an enable period, the MLME-RX-ENABLE.indication is generated upon expiration of the enable period, as specified by the RxOnTime and RxOnDuration parameters of the MLME-RX-Enable.request, when no frame was received during the enable period. In this event, the TimeStamp parameter is set to the value of RxOnTime + RxOnDuration.

NOTE—The reception of a Data frame, or an SP3 format packet, during the enable period is indicated by the MAC using the MCPS-DATA.indication primitive.

8.2.8 Primitives for channel scanning

8.2.8.1 General

These primitives are used to find PANs in a channel, measure the energy in the channel, or do other types of scans.

8.2.8.2 MLME-SCAN.request

The MLME-SCAN.request primitive is used to initiate a channel scan over a given set of channels.

The semantics of this primitive are as follows:

```
MLME-SCAN.request      (
    ScanType,
    ScanChannels,
    ScanDuration,
    SecurityParams,
    LinkQualityScan,
    PanIdSuppressed,
    SeqNumSuppressed,
    HeaderIeList,
    PayloadIeList,
    HeaderIeIdList,
    NestedIeSubIdList,
)
```

The primitive parameters are defined in Table 8-18.

Table 8-18—MLME-SCAN.request parameters

Name	Type	Valid range	Description
ScanType	Enumeration	ED, ACTIVE, PASSIVE, ORPHAN, ENHANCED_ACTIVE_ SCAN, RIT_PASSIVE, MPM_SCAN	Indicates the type of scan performed, as described in 6.4.1.
ScanChannels	List of channel information structures as defined in 11.1.3.1	Any list of valid channels	List of channels to be scanned.
ScanDuration	Integer	0–0xffffffff	A value used for the length of time in symbol periods to spend scanning each channel. This parameter is ignored for orphan scans.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.
LinkQualityScan	Boolean	TRUE, FALSE	If TRUE, Link Quality Scan should be enabled, otherwise FALSE.
PanIdSuppressed	Boolean	TRUE, FALSE	Set to TRUE if the PAN ID is suppressed in the frame, FALSE otherwise.
SeqNumSuppressed	Boolean	TRUE, FALSE	Set to TRUE if the sequence number is suppressed in the frame, FALSE otherwise.
HeaderIeList	List of IEs as described in 7.4.2	—	The header IEs, excluding Termination IEs, to be added to the frame.
PayloadIeList	List of IEs as described in 7.4.3	—	The payload IEs, excluding Termination IEs, to be added to the frame.
HeaderIeIdList	Set of header IE IDs, as described in Table 7-7	—	The IDs of header IEs, excluding Termination IEs, to be added to the frame. The MAC will provide the content for the IE.

Table 8-18—MLME-SCAN.request parameters (continued)

Name	Type	Valid range	Description
NestedIeSubIdList	Set of Nested IE sub-IDs, as described in Table 7-9 and Table 7-10	—	The sub-IDs of nested IEs, excluding Termination IEs, to be added to the frame. The MAC will provide the content for the IE.

When the MLME receives this primitive, it begins the appropriate scan procedure, as defined in 6.4.

The SecurityParams parameter is used only in an orphan scan.

When the ScanType is set to ENHANCED_ACTIVE_SCAN, this primitive is used to initiate an enhanced active scan.

The active scan, as described in 10.19, is performed on each channel by the MLME first sending a Beacon Request command as described in 7.5.2 or an Enhanced Beacon Request command as described in 7.5.3 if using an enhanced active scan. The MLME then enables the receiver and records the information contained in each received beacon in a PAN descriptor structure as described in Table 8-3. The active scan on a particular channel terminates when the number of PAN descriptors stored equals an implementation-specified maximum or when ScanDuration parameter symbols have elapsed, whichever comes first.

8.2.8.3 MLME-SCAN.confirm

The MLME-SCAN.confirm primitive reports the result of the channel scan request.

The semantics of this primitive are as follows:

```
MLME-SCAN.confirm (ScanType, UnscannedChannels, EnergyDetectList, PanDescriptorList, DetectedCategory, Status)
```

The primitive parameters are defined in Table 8-19.

If the requested scan was successful, the Status parameter will be set to SUCCESS.

If the MLME receives the MLME-SCAN.request primitive while performing a previously initiated scan operation, the MLME will not perform the scan, and the Status parameter will be set to SCAN_IN_PROGRESS.

If the MLME receives the MLME-SCAN.request primitive with invalid or incorrect items in the ScanChannels list, it will not perform the scan, and the Status parameter will be set to BAD_CHANNEL.

Table 8-19—MLME-SCAN.confirm parameters

Name	Type	Valid range	Description
ScanType	Integer	ED, ACTIVE, PASSIVE, ORPHAN, ENHANCED_ACTIVE_SCAN, RIT_PASSIVE, MPM_SCAN	As defined in Table 8-18.
UnscannedChannels	List of channel information structures as defined in 11.1.3.1	Any list of valid channels	A list of the channels given in the request that were not scanned.
EnergyDetectList	List of integers	0x00–0xff for each integer	The list of energy measurements, one for each channel searched during an ED scan. For HRP UWB PHY the EnergyDetectList contains separate energy measurements for each channel and for each channel measurement is a list of integers matching fraction of the full channel bandwidth channel. The number of increments is indicated in the <i>phyHrpUwbScanBinsPerChannel</i> PHY PIB attribute.
PanDescriptorList	List of PAN descriptor values	As defined in Table 8-3	The list of PAN descriptors, one for each beacon found during the scan if <i>macAutoRequest</i> is set to TRUE.
DetectedCategory	Integer	0x00–0xff	Categorization of energy detected in channel with the following values: 0: Category detection is not supported 1: HRP UWB PHY detected 2: Non-HRP UWB PHY signal source detected 3–255: Reserved for future use.
Status	Enumeration	SUCCESS, LIMIT_REACHED, NO_BEACON, SCAN_IN_PROGRESS, BAD_CHANNEL, also see 8.2.2	The status of the scan request.

If, during an active scan, the MLME is unable to transmit a Beacon Request command on a channel specified by the ScanChannels parameter due to a channel access failure, the channel will appear in the list of unscanned channels returned by the MLME-SCAN.confirm primitive. If the MLME was able to send a Beacon Request command on at least one of the channels but no beacons were found, the MLME-SCAN.confirm primitive will contain a null set of PAN descriptor values, regardless of the value of *macAutoRequest*, and a Status of NO_BEACON.

If the MLME is unable to transmit an Orphan Notification command on a channel specified by the ScanChannels parameter due to a channel access failure, the channel will appear in the list of unscanned channels returned by the MLME-SCAN.confirm primitive. If the MLME was able to send an Orphan Notification command on at least one of the channels but the device did not receive a Coordinator Realignment command, the MLME-SCAN.confirm primitive will contain a Status of NO_BEACON.

If the MLME-SCAN.request primitive did not request an ED scan, the EnergyDetectList and DetectedCategory parameters will be null. If the MLME-SCAN.request primitive requested an ED or orphan scan, the PanDescriptorList parameter will be null. If the MLME-SCAN.request primitive requested an ED scan the UnscannedChannels will be null.

If, during a scan, the implementation-specified maximum of PAN descriptors is reached thus terminating the scan procedure, the MAC sublayer will issue the MLME-SCAN.confirm primitive with a Status of LIMIT_REACHED.

8.2.9 Primitives for updating the superframe configuration

8.2.9.1 General

These primitives are used by a device to initiate a PAN, to begin using a new superframe configuration, or to stop transmitting beacons. In addition, a device uses these primitives to begin using a new superframe configuration.

8.2.9.2 MLME-START.request

The MLME-START.request primitive is used by the PAN coordinator to initiate a new PAN not using superframe structure.

The semantics of this primitive are as follows:

```
MLME-START.request      (
    PanId,
    ChannelInfo
)
```

The primitive parameters are defined in Table 8-20.

Table 8-20—MLME-START.request parameters

Name	Type	Valid range	Description
PanId	Integer	0x0000–0xffff	The PAN ID to be used by the device.
ChannelInfo	Channel information structure as defined in 11.1.3.1	Any valid channel	The channel to use.

The address used by the coordinator in its beacon frames is determined by the current value of *macShortAddress*, which is set by the next higher layer before issuing this primitive.

8.2.9.3 MLME-START.confirm

The MLME-START.confirm primitive reports the results of the attempt to start a PAN not using superframe structure.

The semantics of this primitive are as follows:

```
MLME-START.confirm      ( 
                           Status
                         )
```

The primitive parameters are defined in Table 8-21.

Table 8-21—MLME-START.confirm parameters

Name	Type	Valid range	Description
Status	Enumeration	SUCCESS, NO_SHORT_ADDRESS, also see 8.2.2	The result of the attempt to start a PAN not using superframe configuration.

The MLME-START.confirm primitive is generated by the MLME and issued to its next higher layer in response to an MLME-START.request primitive. The MLME-START.confirm primitive returns a Status of either SUCCESS, indicating that the MAC sublayer has started a PAN not using superframe structure, or the appropriate error code as follows:

- NO_SHORT_ADDRESS: The *macShortAddress* is set to 0xffff.

8.2.10 Primitives for Beacon Generation

8.2.10.1 MLME-BEACON.request

The MLME-BEACON.request primitive requests the generation of a Beacon frame or Enhanced Beacon frame, either in response to a Beacon Request command or Enhanced Beacon Request command when *macBeaconAutoRespond* is FALSE, or on demand, e.g., to send beacons to enable a TSCH passive scan.

The semantics of this primitive are as follows:

```
MLME-BEACON.request      ( 
                           BeaconType,
                           ChannelInfo,
                           SuperFrameOrder,
                           HeaderList,
                           PayloadList,
                           HeaderIdList,
                           NestedIdSubIdList,
                           BeaconSecurityParam,
                           SrcAddrMode,
                           DstAddrMode,
                           DstAddr,
                           BsnSuppression
                         )
```

The primitive parameters are defined in Table 8-22.

On receipt of the MLME-BEACON.request primitive, the MAC sublayer entity constructs and transmits a beacon or enhanced beacon depending on the value of the BeaconType parameter.

Table 8-22—MLME-BEACON.request parameters

Name	Type	Valid range	Description
BeaconType	Enumeration	BEACON, ENHANCED BEACON	Indicates if the beacon request to be sent is a beacon or an enhanced beacon.
ChannelInfo	Channel Information structure as defined in 11.1.3.1	Any valid channel	The channel to use.
SuperframeOrder	Integer	0–15	The length of the active portion of the superframe, including the beacon frame.
HeaderIeList	List of header IEs as described in 7.4.2	—	The header IEs, excluding Termination IEs, to be included in the Beacon frame. If empty, then no header IEs are included.
PayloadIeList	List of payload IEs as described in 7.4.3	—	The payload IEs, excluding Termination IEs, to be included in the Beacon frame. If empty, then no payload IEs are included.
HeaderIeIdList	List of header IE IDs, as described in Table 7-7	—	The IDs of header IEs, excluding Termination IEs, to be added to the frame. The MAC will provide the content for the IE.
NestedIeSubIdList	List of Nested IE sub-IDs, as described in Table 7-9 and Table 7-10	—	The sub-IDs of nested IEs, excluding Termination IEs, to be added to the Data frame. The MAC will provide the content for the IE.
BeaconSecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.
SrcAddrMode	Enumeration	NONE, SHORT, EXTENDED	The source addressing mode for this MPDU.
DstAddrMode	Enumeration	NONE, SHORT, EXTENDED	The destination addressing mode, as described in 7.2.2.9, for this primitive and subsequent beacon.
DstAddr	Short address or extended address	As specified by the DstAddrMode parameter	If sent in response to an MLME-BEACON-REQUEST.indication, the device who sent the beacon request, otherwise the short broadcast address.
BsnSuppression	Boolean	TRUE, FALSE	If BeaconType is ENHANCED_BEACON, then if BsnSuppression is TRUE, the EBSN is omitted from the frame, and the Sequence Number Suppression field of the Frame Control field is set to one.

The MAC sublayer builds a MAC protocol data unit (MPDU) to transmit from the supplied arguments. The DstAddrMode parameters correspond to the Addressing fields in the Frame Control field, as described in 7.2.2, and are used to construct both the Frame Control and Addressing fields of the MHR.

The frame control and addressing mode options for beacon and enhanced beacons are described in 7.3.1.

The address used by the coordinator in its beacon frames is determined by the current value of *macShortAddress*, which is set by the next higher layer before issuing this primitive.

If BeaconType is set to BEACON, the *macBsn* is used for the sequence number. If BeaconType is set to ENHANCED_BEACON, and BsnSuppression is FALSE, the *macEbsn* is used. If BeaconType is set to ENHANCED_BEACON, and BsnSuppression is TRUE, then the sequence number is omitted, and the Sequence Number Suppression field of the Frame Control field is set to one.

If BeaconType is set to ENHANCED_BEACON, then an enhanced beacon is constructed using the list of IEs in *macEbIeList*, and the IE Present field of the Frame Control field is set to one.

If the length of the beacon frame exceeds *phyMaxPacketSize* (e.g., due to the additional overhead required for security processing), the MAC sublayer shall discard the beacon frame and issue the MLME-BEACON.confirm primitive with a Status of FRAME_TOO_LONG.

If the transmission uses CSMA-CA and the CSMA-CA algorithm failed due to adverse conditions on the channel, and the TxOptions parameter specifies that a direct transmission is required, the MAC sublayer will discard the MSDU and issue the MLME-BEACON.confirm primitive with a Status of CHANNEL_ACCESS_FAILURE.

If the MPDU was successfully transmitted and, if requested, an acknowledgment was received, the MAC sublayer will issue the MLME-BEACON.confirm primitive with a Status of SUCCESS.

If any parameter in the MLME-BEACON.request primitive is not supported or is out of range, the MAC sublayer will issue the MLME-BEACON.confirm primitive with a Status of INVALID_PARAMETER.

8.2.10.2 MLME-BEACON.confirm

The semantics of this primitive are as follows:

```
MLME-BEACON.confirm      ( 
                           Status
                           )
```

The primitive parameter is defined in Table 8-23.

Table 8-23—MLME-BEACON.confirm parameters

Name	Type	Valid range	Description
Status	Enumeration	SUCCESS, also see 8.2.2	The result of the attempt to send the beacon or enhanced beacon.

The MLME-BEACON.confirm primitive is generated by the MAC sublayer entity in response to an MLME-BEACON.request primitive. The MLME-BEACON.confirm primitive returns a Status of either SUCCESS, indicating that the request to transmit was successful, or the appropriate error code. The Status values are fully described in 8.2.10.1.

On receipt of the MLME-BEACON.confirm primitive, the higher layer is notified of the result of its request to transmit a beacon or enhanced beacon. If the transmission attempt was successful, the Status parameter will be set to SUCCESS. Otherwise, the Status parameter will indicate the error. If an enhanced beacon was requested, and the device does not support enhanced beacons, INVALID_PARAMETER will be returned.

8.2.10.3 MLME-BEACON.indication

The semantics of this primitive are as follows:

```
MLME-BEACON.indication (Timestamp)
```

The primitive parameters are defined in Table 8-24.

Table 8-24—MLME-BEACON.indication parameters

Name	Type	Valid range	Description
TimeStamp	Integer	0x000000–0xffffffff	The time when the beacon was transmitted. The format of timestamp is specified in 6.5.3.

The MLME-BEACON.indication primitive is optional for non-ERDEV. It is generated by the MLME to inform the next higher layer that a beacon frame has been sent.

8.2.10.4 MLME-BEACON-REQUEST.indication

The MLME-BEACON-REQUEST.indication primitive indicates the receipt of a Beacon Request command or an Enhanced Beacon Request command. It is only available when *macBeaconAutoRespond* is FALSE.

The semantics of this primitive are as follows:

```
MLME-BEACON-REQUEST.indication(
    BeaconType,
    SrcAddrMode,
    SrcAddr,
    DstPanId,
    HeaderList,
    PayloadList
)
```

The primitive parameters are defined in Table 8-25.

Table 8-25—MLME-BEACON-REQUEST.indication parameters

Name	Type	Valid range	Description
BeaconType	Enumeration	BEACON, ENHANCED BEACON	Indicates if the beacon request was for a beacon or an enhanced beacon.
SrcAddrMode	Enumeration	NONE, SHORT, EXTENDED	The source addressing mode, as described in 7.2.2.11, for device from whom the beacon request was received.
SrcAddr	Short address or extended address	As specified by the SrcAddrMode parameter	The device who sent the beacon request, if present; otherwise, the short broadcast address.

Table 8-25—MLME-BEACON-REQUEST.indication parameters (continued)

Name	Type	Valid range	Description
DstPanId	Integer	0x0000–0xffff	The PAN ID contained in the beacon request, or the broadcast PAN ID if PAN ID not present.
HeaderIeList	Set of header IEs as described in 7.4.2	—	The header IEs, excluding Termination IEs, to be included in the Beacon frame. If empty, then no header IEs are included.
PayloadIeList	Set of payload IEs as described in 7.4.3	—	The payload IEs, excluding Termination IEs, to be included in the Beacon frame. If empty, then no payload IEs are included.

The MLME-BEACON-REQUEST.indication primitive is generated by the MAC sublayer and issued to a higher layer on receipt of a beacon request or enhanced beacon request. The MLME-BEACON-REQUEST.indication is only generated when *macBeaconAutoRespond* is FALSE.

A higher layer can use the information contained in the MLME-BEACON-REQUEST.indication to construct and send a beacon or enhanced beacon using the MLME-BEACON.request primitive.

8.3 MAC data service

8.3.1 General

The MCPS-SAP supports the transport of data. Table 8-26 lists the primitives supported by the MCPS-SAP. Primitives marked with a asterisk (*) are optional. These primitives are discussed in the subclauses referenced in the table.

Table 8-26—MCPS-SAP primitives

MCPS-SAP primitive	Request	Confirm	Indication
MCPS-DATA	8.3.4	8.3.5	8.3.6
MCPS-PURGE	8.3.7*	8.3.8*	—
MCPS-RANGING-VERIFIER	10.33.8.1.1*	10.33.8.1.2*	10.33.8.1.3*
MCPS-RANGING-PROVER	10.33.8.2.1*	10.33.8.2.2*	10.33.8.2.3*

8.3.2 Ranging

8.3.2.1 General

In parallel to their data transfer utility, Data frame (and Ack frame) transmission and reception events notified by the MCPS-DATA primitives are also used by RDEVs for ranging and localization as described in 10.29. These primitives include a number of parameters specifically for this localization utility. For example, the MCPS-DATA.indication in an RDEV conveying sensor data from a remote device can also

have an associated time of arrival, AOA, and other supporting parameters that may be used to locate the sender.

The HRP-ERDEV has a number of packet configurations, see 16.2, including SP3 where the PPDU consists of SHR and STS only (i.e., no PHR or data). Even though no Data frame is sent or received when using SP3 packets, the MCPS-DATA primitives are used to control and report the sending and reception of these packets because the higher layer logically uses these primitives for ranging, and needs the ranging associated parameters carried by these primitives along with any data that may be conveyed when not using SP3 packets. The next higher layer is in control of selecting the SP3 packet configuration and therefore knows not to supply or expect an MSDU in the MCPS-DATA primitives. Architecturally, an SP3 packet may be considered to be a broadcast frame. The transmitting HRP-ERDEV reports the sending of an SP3 packet via the MCPS-DATA.confirm primitive whose TxRangingCounter value within the RangingReportDescriptor (defined in Table 8-28) parameter provides the ranging marker (RMARKER) send time, and the receiving HRP-ERDEV reports its arrival conveying the RxRangingCounter (and other localization related values) in the RangingReportDescriptor parameter MCPS-DATA.indication. The higher layer can use the figure of merit (FoM) associated with the STS to assess the level of STS correlation, and validate the integrity of the STS based receive time and confirm the STS is from the expected sender (i.e., has been generated using the correct seed information).

Ranging related parameters in the MCPS-DATA primitives are in separate structures, DataRequestRangingDescriptor and RangingReportDescriptor.

8.3.2.2 DataRequestRangingDescriptor

The elements of the DataRequestRangingDescriptor are defined in Table 8-27.

Table 8-27—Elements of the DataRequestRangingDescriptor

Name	Type	Valid range	Description
Ranging	Boolean	TRUE, FALSE	The ranging counter is enabled for ranging operations if this is TRUE, and disabled if it is FALSE.
RangingPhr	Boolean	TRUE, FALSE	TRUE if the Ranging field of PHR is set to be one, FALSE otherwise. This parameter is only valid when the PHR is present and has a Ranging field.
TxTimeSpecified	Enumeration	NONE, RCTU_TIME, RSTU_TIME	Specifies whether the RangingTxTime parameter is used to control the time of transmission the frame and the units. If TxTimeSpecified is NONE, the transmission time is not specified by the Ranging Tx Time.
RangingTxTime	Unsigned Integer	0x00000000–0xffffffff	Specifies the transmit time for the frame as follows: When TxTimeSpecified is RCTU_TIME, this parameter specifies the RMARKER transmit time in the units defined in 10.29.1.4. When TxTimeSpecified is RSTU_TIME, this parameter specifies the time to start transmitting the packet in the units defined in 10.29.1.5. When TxTimeSpecified is equal to NONE, this parameter is not used to specify the transmit time.

Table 8-27—Elements of the DataRequestRangingDescriptor (continued)

Name	Type	Valid range	Description
RequestRtiTxList	List of {Address, Ranging Counter} pairs.	Each pair is a Short or Extended address, along with a ranging counter value in the range 0x00000000–0xffffffff	Provides a list of nodes for which RRTI IEs are requested, along with the receive ranging counter values of their messages for which each respective RRTI IE is to be generated. If the list is empty then no RRTI IEs are transmitted.
LocationEnhancingInformationPostamble	Enumeration	LEIP_NONE, LEIP_IMMEDIATE, LEIP_DELAYED	For the LRP UWB PHY this parameter specifies whether the Location enhancing information postamble sequence is to be sent or not and, if present, whether it directly follows the CRC or is delayed by the <i>aLeipDelayTime</i> . A value of LEIP_NONE is used for non-LRP UWB PHYs.
LocationEnhancingInformationPostambleLength	Enumeration	LEIP_LEN_16, LEIP_LEN_64, LEIP_LEN_128, LEIP_LEN_192, LEIP_LEN_256, LEIP_LEN_512, LEIP_LEN_1024	For the LRP UWB PHY when the LocationEnhancingInformationPostamble parameter has a value of either LEIP_IMMEDIATE or LEIP_DELAYED, then this parameter specifies the length in pulses of the location enhancing information postamble to send. This parameter is ignored when the LocationEnhancingInformationPostamble parameter has a value of LEIP_NONE.

If RequestRtiTxList is non-empty and the MAC has the capability to generate an RRTI IE, the MAC sublayer shall insert the RRTI IE (as described in 10.29.8.1) into the frame prior to sending it, using the address/ranging counter pairs from the RequestRtiTxList parameter, to form each RRTI List element, calculating the appropriate RX-to-TX Reply Time field value as the difference between the transmitted frame's RMARKER time and the corresponding receive ranging counter value from the RequestRtiTxList. Each RRTI List element's address field shall be the corresponding address from the RequestRtiTxList. The RRTI IE's address field may be omitted in the case of unicast ranging (where the RequestRtiTxList parameter contains a single address/ranging counter pair) since the address is in the MHR. If the MAC does not have the capability to send an RRTI IE, the transmission shall fail and the MAC sublayer shall discard the MSDU and issue the MCPS-DATA.confirm primitive with a status of UNSUPPORTED_FEATURE.

If TxTimeSpecified is RCTU_TIME, the MAC sublayer shall transmit the packet with its RMARKER at the time specified by the RangingTxTime parameter with reference to the running ranging counter units as defined in 10.29.1.4. If ranging is not enabled or this constraint cannot be met (i.e., the specified value is more than half the counter period in the future, in which case the MAC shall consider this to be a late invocation), the MAC sublayer will discard the MSDU and issue the MCPS-DATA.confirm primitive with a status of UNSUPPORTED_FEATURE or TX_TIME_ERROR as appropriate.

If TxTimeSpecified is RSTU_TIME, the device shall send the packet with the start time (of preamble) as specified by the RangingTxTime, with reference to the RSTU time counter units as defined in 10.29.1.5. If the specified value is more than half a period in the future, the MAC shall consider this to be a late invocation and the MAC sublayer will discard the MSDU and issue the MCPS-DATA.confirm primitive with a status of TX_TIME_ERROR. For an RDEV, when the Ranging parameter enables the ranging counter to do ranging operations, it stays enabled until disabled by either a subsequent MCPS-DATA.request or an MLME-RX-ENABLE.request. While ranging is enabled, RMARKER transmission and reception times are reported via the TxRangingCounter and RxRangingCounter values within the

RangingReportDescriptor (defined in Table 8-28) parameter of the MCPS-DATA.confirm and MCPS-DATA.indication primitives.

8.3.2.3 RangingReportDescriptor

The elements of the RangingReportDescriptor structure are defined in Table 8-28.

Table 8-28—Elements of the RangingReportDescriptor

Name	Type	Valid range	Description
RangingReceived	Enumeration	NOT_REQUESTED, RANGING_ACTIVE, NOT_SUPPORTED	This value indicates the result of receiving the Ranging field of the PHR as follows: A value of NOT_REQUESTED indicates that no ranging is requested for the PSDU received. A value of RANGING_ACTIVE indicates that ranging was requested for the received PSDU. A value of NOT_SUPPORTED indicates that ranging is not supported but has been requested.
RxRangingCounter	Unsigned Integer	0x00000000–0xffffffff	A count of the time units corresponding to an RMARKER at the antenna with respect to the reception of a ranging packet. The units of time are specified in 10.29.1.4.
TxRangingCounter	Unsigned Integer	0x00000000–0xffffffff	A count of the time units corresponding to an RMARKER at the antenna with respect to the transmission of a ranging packet. The units of time are specified in 10.29.1.4.
RangingTrackingInterval	Unsigned Integer	0x00000000–0xffffffff	A count of the time units over which the tracking offset was measured during the reception of a ranging packet, as described in 10.29.1.6.3. This value is invalid if tracking-based crystal characterization is not supported.
RangingOffset	Integer	0x00000000–0xffffffff	A count of the time units slipped or advanced by the radio tracking system over the course of the entire RangingTrackingInterval. This is described in 10.29.1.6.2. This value is invalid if tracking-based crystal characterization is not supported.
RangingFom	Unsigned Integer	0x00–0xff	The FoM characterizing the RxRangingCounter value, as described in 10.29.1.7.
AngleOfArrivalAzimuth	Float	−π to +π	When <i>macAoaEnable</i> is TRUE, this is the AOA in radians of the received signal in azimuth measured during the reception of a ranging packet. This value is valid only when AngleOfArrivalSupported is either AZIMUTH or BOTH. The real world direction indicated (e.g., by zero radians) is a system set-up parameter beyond the scope of this standard.

Table 8-28—Elements of the RangingReportDescriptor (continued)

Name	Type	Valid range	Description
AngleOfArrivalElevation	Float	$-\pi/2$ to $+\pi/2$	When <i>macAoaEnable</i> is TRUE, this is the AOA in radians of the received signal in elevation measured during the reception of a ranging packet. This value is valid only when AngleOfArrivalSupported is set to either ELEVATION or BOTH.
AngleOfArrivalSupported	Enumeration	NONE, BOTH, AZIMUTH, ELEVATION	Indicates the validity of AngleOfArrivalAzimuth and AngleOfArrivalElevation values. Where the underlying PHY does not support AOA measurement, then this value shall be NONE.
RxS0RangingCounter	Unsigned Integer	0x00000000–0xffffffff	A count of the time units corresponding to an SRMARKER0 at the antenna with respect to the reception of a ranging packet. The units of time are specified in 10.29.1.4. This value is invalid if the SRMARKER0 was not present.
RxS1RangingCounter	Unsigned Integer	0x00000000–0xffffffff	A count of the time units corresponding to an SRMARKER1 at the antenna with respect to the reception of a ranging packet. The units of time are specified in 10.29.1.4. This value is invalid if the SRMARKER1 was not present.
RxS2RangingCounter	Unsigned Integer	0x00000000–0xffffffff	A count of the time units corresponding to an SRMARKER2 at the antenna with respect to the reception of a ranging packet. The units of time are specified in 10.29.1.4. This value is invalid if the SRMARKER2 was not present.
RxS3RangingCounter	Unsigned Integer	0x00000000–0xffffffff	A count of the time units corresponding to an SRMARKER3 at the antenna with respect to the reception of a ranging packet. The units of time are specified in 10.29.1.4. This value is invalid if the SRMARKER3 was not present.
RxS4RangingCounter	Unsigned Integer	0x00000000–0xffffffff	A count of the time units corresponding to an SRMARKER4 at the antenna with respect to the reception of a ranging packet. The units of time are specified in 10.29.1.4. This value is invalid if the SRMARKER4 was not present.
TxS0RangingCounter	Unsigned Integer	0x00000000–0xffffffff	A count of the time units corresponding to an SRMARKER0 at the antenna with respect to the transmission of a ranging packet. The units of time are specified in 10.29.1.4. This value is invalid if the SRMARKER0 was not sent.
TxS1RangingCounter	Unsigned Integer	0x00000000–0xffffffff	A count of the time units corresponding to an SRMARKER1 at the antenna with respect to the transmission of a ranging packet. The units of time are specified in 10.29.1.4. This value is invalid if the SRMARKER1 was not sent.

Table 8-28—Elements of the RangingReportDescriptor (continued)

Name	Type	Valid range	Description
TxS2RangingCounter	Unsigned Integer	0x00000000–0xffffffff	A count of the time units corresponding to an SRMARKER2 at the antenna with respect to the transmission of a ranging packet. The units of time are specified in 10.29.1.4. This value is invalid if the SRMARKER2 was not sent.
TxS3RangingCounter	Unsigned Integer	0x00000000–0xffffffff	A count of the time units corresponding to an SRMARKER3 at the antenna with respect to the transmission of a ranging packet. The units of time are specified in 10.29.1.4. This value is invalid if the SRMARKER3 was not sent.
TxS4RangingCounter	Unsigned Integer	0x00000000–0xffffffff	A count of the time units corresponding to an SRMARKER4 at the antenna with respect to the transmission of a ranging packet. The units of time are specified in 10.29.1.4. This value is invalid if the SRMARKER4 was not sent.
RangingStsFom	Array of four Unsigned Integers	0 to 255	An array of four values with respect to the reception of a ranging packet, one value for each STS segment, in order of reception. Each reports a percentage measurement of the correlation strength between the received STS segment and the expected internally generated reference STS segment, where a value of 255 means 100%, a zero value is special and means no FoM value is provided. The values corresponding to a particular STS segment are only valid when the device is configured to expect the segment.
RangingStsAoaAzimuthFom	Unsigned Integer	0 to 255	An FoM with respect to the expected accuracy of the AOA estimate in azimuth based on the received STS, where a value of 255 corresponds to a combination of high implementation accuracy and a high signal quality in the received STS. This parameter is valid only when AngleOfArrivalSupported is AZIMUTH or BOTH. The value of 0x00 is special meaning no FoM is provided.
RangingStsAoaElevationFom	Unsigned Integer	0 to 255	An FoM with respect to the expected accuracy of the AOA estimate in elevation based on the received STS, where a value of 255 corresponds to a combination of high implementation accuracy and a high signal quality in the received STS. This parameter is valid only when AngleOfArrivalSupported is ELEVATION or BOTH. The value of 0x00 is special meaning no FoM is provided.

This is a parameter used in both the MCPS-DATA.confirm primitive and the MCPS-DATA.indication primitive. For the MCPS-DATA.confirm primitive, the elements of the RangingReportDescriptor relating to transmission are for the packet transmitted as a result of the corresponding MCPS-DATA.request, while the elements relating to reception are with respect to the Ack frame (if solicited in the MCPS-DATA.request).

and are invalid if an Ack frame was not received. For the MCPS-DATA.indication primitive, the elements of the RangingReportDescriptor relating to reception are for the packet reception being reported by the primitive, while elements relating to transmission are with respect to the transmission of an Ack frame (if one was solicited by the frame being delivered), and are invalid if an Ack frame was not sent.

In the case of an HRP-ERDEV configured to use SP3 format packets, the following applies: the reception of a packet shall be treated like the receipt of a broadcast RFRAFME; the RxS0RangingCounter, RxS1RangingCounter, and RangingStsFom (for STS segment 1) elements of the RangingReportDescriptor (defined in Table 8-28) shall be provided, while all other ranging related values are optional and dependent on the capability of the RDEV to support them. The MCPS-DATA.indication primitive parameters associated with the absent PHR and MAC Frame shall set appropriately empty (the higher layer in any case should not be expecting these when it has configured the use of SP3 packets).

The use of ranging counters is described in “Application of IEEE Std 802.15.4” [B4].

8.3.3 TxOptions

The TxOptions structure contains specific parameters related to the transmission parameters of frame. The elements of the TxOptions are defined in Table 8-29.

Table 8-29—Elements of the TxOptions

Name	Type	Valid range	Description
AckTx	Boolean	TRUE, FALSE	TRUE if acknowledged transmission is used, FALSE otherwise.
GtsTx	Boolean	TRUE, FALSE	TRUE if a GTS is to be used for transmission. FALSE indicates that the CAP will be used.
IndirectTx	Boolean	TRUE, FALSE	TRUE if indirect transmission is to be used, FALSE otherwise.
UwbPrf	Enumeration	PRF_OFF, NOMINAL_4_M, NOMINAL_16_M, NOMINAL_64_M	The pulse repetition value of the transmitted PPDU. Non-HRP UWB PHYs use a value of PRF_OFF.
UwbPreambleSymbolRepetitions	Integer	0, 16, 32, 64, 128, 256, 512, 1024, 4096, 8192	The preamble symbol repetitions of the HRP UWB PHY or LRP UWB frame. A zero value is used for all other PHYs (see NOTE).
DataRate	Integer	0–7	Indicates the data rate.
PanIdSuppressed	Boolean	TRUE, FALSE	Set to TRUE if the PAN ID is suppressed in the frame, FALSE otherwise.
SeqNumSuppressed	Boolean	TRUE, FALSE	Set to TRUE if the sequence number is suppressed in the frame, FALSE otherwise.
SendMultipurpose	Boolean	TRUE, FALSE	If TRUE, use a Multipurpose frame. If FALSE, use a Data frame.
FrakPolicy	Integer	0b00–0b10	Specifies the Frak policy to be employed, as described in 10.15.2.1. This parameter is only used when MPDU fragmentation is enabled.

Table 8-29—Elements of the TxOptions (continued)

Name	Type	Valid range	Description
CriticalEventMessage	Boolean	TRUE, FALSE	A value of TRUE indicates that the message shall be processed as a critical event message, as described in 10.10.2.1. A value of FALSE indicates that the message is not a critical event message and shall be processed as described in 6.3.2.1.
LegacyTx	Boolean	TRUE, FALSE	TRUE if the Msdu is to be transmitted using the legacy Data frame format with Frame Version field set to 0b01, FALSE otherwise.
EmptyPayload	Boolean	TRUE, FALSE	TRUE if the MAC is not to provide any payload to the PHY, (i.e, the Frame Length field of the PHR is to be zero), FALSE otherwise.

For the DataRate element of the TxOptions structure, the following values are used:

- For CSS PHYs, a value of one indicates 250 kb/s while a value of two indicates 1 Mb/s.
- For HRP UWB PHYs, values 1–4 are valid and are defined in 16.2.7.
- For LRP UWB PHYs, valid values are defined in Table 19-1.
- For the SUN OFDM PHY, values 1–7 are valid; each data rate value corresponds to the variable modulation and coding scheme (MCS) {DataRate–1}, as described in Table 21-10.
- For the SUN O-QPSK PHY with direct sequence spread spectrum (DSSS) spreading, values 1–4 are valid; each data rate value corresponds to the Rate Mode plus one, as described in Table 22-1.
- For the SUN O-QPSK PHY with multiplexed direct sequence spread spectrum (MDSSS) spreading, values 5–8 are valid; each data rate value corresponds to the Rate Mode plus five, as described in Table 22-1.
- For MSK PHYs, valid values are defined in Table 18-1.
- For TASK PHYs, values 0–7 are valid: each value corresponds to the MCS mode as described in 31.3 (given in Table 31-5, Table 31-6, and Table 31-7).
- For RS-GFSK PHYs, values 0–7 are valid; each value corresponds to the MCS mode as described in 32.2 (given in Table 32-2).
- For all other PHYs, the parameter is set to zero.

8.3.4 MCPS-DATA.request

The MCPS-DATA.request primitive requests transmission to another device.

The semantics of this primitive are as follows:

```
MCPS-DATA.request      (
    SrcAddrMode,
    DstAddrMode,
    DstPanId,
    DstAddr,
    Msdu,
    MsduHandle,
    HeaderIeList,
    PayloadIeList,
    HeaderIeIdList,
    NestedIdleSubIdList,
    TxOptions,
    SecurityParams,
    DataRequestRangingDescriptor
)
```

The primitive parameters are defined in Table 8-30.

Table 8-30—MCPS-DATA.request parameters

Name	Type	Valid range	Description
SrcAddrMode	Enumeration	NONE, SHORT, EXTENDED	The source addressing mode for this MPDU.
DstAddrMode	Enumeration	NONE, SHORT, EXTENDED	The destination addressing mode for this MPDU.
DstPanId	Integer	0x0000–0xffff	The PAN ID of the entity to which the MSDU is being transferred.
DstAddr	—	As specified by the DstAddrMode parameter	The address of the entity to which the MSDU is being transferred.
Msdu	Set of octets	—	The set of octets forming the MSDU to be transmitted by the MAC sublayer entity.
MsduHandle	Integer	0x00–0xff	The handle associated with the MSDU to be transmitted by the MAC sublayer entity.
HeaderIeList	Set of IEs as described in Table 7-7	As defined in Table 7-7	The header IEs, excluding Termination IEs, that are to be included with the frame in addition to any header IEs added by the MAC. If empty, no additional header IEs are to be included.
PayloadIeList	Set of IEs as described in Table 7-8	As defined in Table 7-8	The payload IEs, excluding Termination IEs, that are to be included with the frame in addition to any payload IEs added by the MAC. If empty, no additional payload IEs are to be included.
HeaderIeIdList	Set of header IE IDs, as described in Table 7-7	—	The IDs of header IEs, excluding Termination IEs, to be added to the Data frame. The MAC will provide the content for the IE.

Table 8-30—MCPS-DATA.request parameters (continued)

Name	Type	Valid range	Description
NestedIeSubIdList	Set of Nested IE sub-IDs, as described in Table 7-9 and Table 7-10	—	The sub-IDs of nested IEs, excluding Termination IEs, to be added to the Data frame. The MAC will provide the content for the IE.
TxOptions	Structure	As defined in Table 8-29	As defined in Table 8-29.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.
DataRequestRangingDescriptor	Structure	As in Table 8-27	Provides ranging related parameters.
NOTE—Some values may be unsupported or invalid depending on the capabilities of the PHY or its current transmission mode as selected by other parameters.			

On receipt of the MCPS-DATA.request primitive, the MAC sublayer entity begins the transmission of the supplied MSDU.

The TxOptions parameter indicates the method used by the MAC sublayer data service to transmit the supplied MSDU.

If an acknowledged transmission is required (AckTx of TxOptions is TRUE), the AR field will be set appropriately, as described in 6.6.3.

If a GTS transmission is required (GtsTx of TxOptions is TRUE), the MAC sublayer will determine whether it has a valid GTS as described 10.25.4. If a valid GTS could not be found, the MAC sublayer will discard the MSDU. If a valid GTS was found, the MAC sublayer will defer, if necessary, until the GTS. Specifying a GTS transmission in the TxOptions parameter overrides an indirect transmission request.

If an indirect transmission is required (IndirectTx of TxOptions is TRUE) and this primitive is received by the MAC sublayer of a coordinator, the Data frame is sent using indirect transmission, as described in 10.22.

If an indirect transmission is required and if the device receiving this primitive is not a coordinator, the destination address is not present, or a GTS transmission is requested, the indirect transmission option will be ignored.

If SendMultipurpose of TxOptions is TRUE, then the Msdu is to be sent using a Multipurpose frame.

If SendMultipurpose of TxOptions is FALSE, then the Msdu is to be sent using a Data frame.

If LegacyTx of TxOptions is TRUE, the Data frame sent shall use the Frame Version field set to 0b01 and use the IEEE Std 802.15.4-2006 format.

If EmptyPayload of TxOptions is TRUE, the payload delivered to the PHY shall be empty, i.e., have zero length.

The DataRequestRangingDescriptor structure groups the ranging related parameters for the MCPS-DATA.request primitive.

8.3.5 MCPS-DATA.confirm

The MCPS-DATA.confirm primitive reports the results invoking the MCPS-DATA.request primitive.

The semantics of the MCPS-DATA.confirm primitive are as follows:

```
MCPS-DATA.confirm      (
    MsduHandle,
    Timestamp,
    RangingReportDescriptor,
    NumBackoffs,
    HeaderIeList,
    PayloadIeList,
    AckPayload,
    FramePending,
    Rssi,
    Status
)
```

The primitive parameters are defined in Table 8-31.

Table 8-31—MCPS-DATA.confirm parameters

Name	Type	Valid range	Description
MsduHandle	Integer	0x00–0xff	The handle associated with the MSDU being confirmed.
Timestamp	Integer	0x000000–0xffffffff	The time when the data were transmitted. The format of timestamp is specified in 6.5.3. The value of this parameter will be considered valid only if the value of the Status parameter is SUCCESS.
RangingReportDescriptor	Structure	As defined in Table 8-28	Reports ranging related results. This parameter is invalid if ranging is not supported or not enabled.
NumBackoffs	Integer	0x00–0xff	The number of times the CSMA-CA algorithm was required to backoff as described in 6.3.2.1 while attempting the current transmission. If “Status” is anything other than “SUCCESS”, this value is undefined.
HeaderIeList	Set of header IEs as described in 7.4.2	—	The header IEs, excluding Termination IEs, that were included in the Enh-Ack frame, if present.
PayloadIeList	Set of payload IEs as described in 7.4.3	—	The payload IEs, excluding Termination IEs, that were included in the Enh-Ack frame, if present.
AckPayload	Set of octets	—	The set of octets received in the Frame Payload field of the Ack frame, if present.
FramePending	Boolean	—	The Frame pending field value from the incoming Ack frame.

Table 8-31—MCPS-DATA.confirm parameters (continued)

Name	Type	Valid range	Description
Rssi	Boolean	—	For an acknowledged transmission, this reports the received signal strength for the Ack frame. This is a measure of the RF power level at the antenna based on the gain setting in the RX chain and the measured signal level in the channel. For the UWB PHY, the RSSI value is measured during the frame Preamble and locked when a valid SFD is detected. A value of zero indicates that RSSI measurement is not supported or was not measured for this frame.
Status	Enumeration	SUCCESS, INVALID_ADDRESS, INVALID_GTS, UNSUPPORTED FEATURE, UNSUPPORTED_PRF, UNSUPPORTED_RANGING, UNSUPPORTED_PSR, UNSUPPORTED_DATARATE, UNSUPPORTED_LEIP, ACK_RCVD_NODSN_NOSA, TX_TIME_ERROR, also see 8.2.2	The status of the last requested transmission.

The MCPS-DATA.confirm primitive is generated by the MAC sublayer entity in response to an MCPS-DATA.request primitive. The MCPS-DATA.confirm primitive returns a Status of either SUCCESS, indicating that the request to transmit was successful, or the appropriate error code.

If the generated MAC frame is a Data frame with the Frame Version subfield set to 0b00 or 0b01, and both the SrcAddrMode and the DstAddrMode parameters are set to NONE in the MCPS-DATA.request primitive, the Status shall be set to INVALID_ADDRESS.

If a valid GTS could not be found, the Status shall be set to INVALID_GTS.

If there is no capacity to store the transaction, the Status will be set to TRANSACTION_OVERFLOW.

If the transaction is not handled within the required time, the transaction information will be discarded and the Status will be set to TRANSACTION_EXPIRED.

If the TxOptions parameter specifies that a direct transmission is required and the MAC sublayer does not receive an acknowledgment from the recipient after *macMaxFrameRetries* retransmissions, as described in 6.6.3, it will discard the MSDU and issue the MCPS-DATA.confirm primitive with a Status of NO_ACK.

If the requested transaction is too large to fit in the CAP or GTS, as appropriate, the MAC sublayer shall discard the frame and issue the MCPS-DATA.confirm primitive with a Status of FRAME_TOO_LONG. If the length of the frame exceeds *phyMaxPacketSize* (e.g., due to the additional overhead required for security processing or additional IEs), the MAC sublayer shall discard the frame and issue the MCPS-DATA.confirm primitive with a Status of FRAME_TOO_LONG.

If the transmission uses CSMA-CA and the CSMA-CA algorithm failed due to adverse conditions on the channel, and the TxOptions parameter specifies that a direct transmission is required, the MAC sublayer will discard the MSDU, and the Status will be set to CHANNEL_ACCESS_FAILURE.

If an acknowledgment is received without a DSN or Source Address field, the Status will be set to ACK_RCVD_NODSN_NOSA.

If an acknowledgment is received that contains user data encapsulated in IEs or included in the Payload field, the received AckPayload, HeaderIeList, and PayloadIeList will contain the received data.

If the MAC PIB attributes *macPriorityChannelAccess* or *macPcaAllocationSuperRate* are set differently from their respective conditions in Table 10-63, or if the attribute *macPcaAllocationRate* does not satisfy the minimum value defined by its respective condition in Table 10-63, then the MAC sublayer may discard the PCA MSDU and set the Status of the MCPS-DATA.confirm primitive to INVALID_PARAMETER.

If the MAC PIB attribute *macPriorityChannelAccess* is set to FALSE, the MAC sublayer will discard the PCA MSDU and the Status of the MCPS-DATA.confirm primitive will be set to INVALID_PARAMETER.

If some parameters to the MCSP-DATA.request are not supported, the MAC indicates this by issuing the MCPS-DATA.confirm primitive with one of the following Status values:

- UNSUPPORTED_DATARATE: The DataRate requested is not supported.
- UNSUPPORTED_LEIP: The LocationEnhancingInformationPostamble or LocationEnhancingInformationPostambleLength parameter values are not supported.
- UNSUPPORTED_PRF: The UwbPrf parameter value is not supported.
- UNSUPPORTED_PSR: The UwbPreambleSymbolRepetitions value is not supported.
- RANGING_NOT_SUPPORTED: The Ranging is not supported.

In the case of an HRP-ERDEV configured to use SP3 format packets, the MCPS-DATA.confirm primitive shall indicate the completion of the transmission and deliver the TxRangingCounter to the higher layer, via the RangingReportDescriptor parameter.

The use of ranging counters is described in “Application of IEEE Std 802.15.4” [B4].

8.3.6 MCPS-DATA.indication

The MCPS-DATA.indication primitive indicates the reception of data from another device or, when ranging information is available, upon reception of a packet from another device.

The semantics of this primitive are as follows:

MCPS-DATA.indication	(
	SrcAddrMode,
	SrcPanId,
	SrcAddr,
	DstAddrMode,
	DstPanId,
	DstAddr,
	Msdu,
	HeaderIeList,
	PayloadIeList,
	MpduLinkQuality,
	Dsn,
	FramePending,
	Timestamp,
	SecurityParams,
	AckSent,

```

        RangingReportDescriptor,
        DataRate,
        DataFrameVersion,
        EmptyPayload,
        Rssi
    )

```

The primitive parameters are defined in Table 8-32.

Table 8-32—MCPS-DATA.indication parameters

Name	Type	Valid range	Description
SrcAddrMode	Enumeration	NONE, SHORT, EXTENDED	The source addressing mode for this primitive corresponding to the received MPDU.
SrcPanId	Integer	0x0000–0xffff	The PAN ID of the entity from which the MSDU was received. Valid only when a source PAN ID is included in the received frame.
SrcAddr	—	As specified by the SrcAddrMode parameter	The address of the entity from which the MSDU was received.
DstAddrMode	Enumeration	NONE, SHORT, EXTENDED	The destination addressing mode for this primitive corresponding to the received MPDU.
DstPanId	Integer	0x0000–0xffff	The PAN ID of the entity to which the MSDU is being transferred. Set to the receiver's PAN ID if the PAN ID is not carried in the received frame.
DstAddr	—	As specified by the DstAddrMode parameter	The address of the entity to which the MSDU is being transferred.
Msdu	Set of octets	—	The set of octets forming the MSDU being indicated by the MAC sublayer entity including payload IEs if present.
HeaderIeList	Set of header IEs as described in 7.4.2	—	The header IEs, excluding Termination IEs, that were included in the MAC frame. If empty, then no header IEs were in the MAC frame.
PayloadIeList	Set of payload IEs as described in 7.4.3	—	The payload IEs, excluding Termination IEs, that were included in the MAC frame. If empty, then no payload IEs were in the MAC frame.
MpduLinkQuality	Integer	0x00–0xff	LQI value measured during reception of the MPDU. Lower values represent lower LQI, as described in 11.2.7.
Dsn	Integer	0x00–0xff	The DSN of the received Data frame if one was present.
Framepending	Boolean	TRUE/FALSE	The value of the frame pending field of the received frame control field.
Timestamp	Integer	0x000000–0xffffffff	The time at which the data were received. The format of timestamp is specified in 6.5.3.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

Table 8-32—MCPS-DATA.indication parameters (continued)

Name	Type	Valid range	Description
AckSent	Boolean	TRUE, FALSE	TRUE if the received frame requested an acknowledgment that has been sent, FALSE otherwise.
RangingReportDescriptor	Structure	As defined in Table 8-28	Reports ranging related results. The parameter is invalid if ranging is not supported or not enabled.
DataRate	Integer	—	As defined in 8.3.3.
DataFrameVersion	Integer	0b00–0b11	Indicates the Frame Version field of the received frame.
EmptyPayload	Boolean	TRUE, FALSE	TRUE if the received PHR indicated zero length payload, (in which case the MAC frame related parameters are invalid), FALSE otherwise.
Rssi	Integer	0x00–0xff	The Received Signal Strength Indicator is a measure of the RF power level at the input of the transceiver measured during the SHR and is valid after the SFD is detected.

The MCPS-DATA.indication primitive is generated by the MAC sublayer and issued to the next higher layer on receipt of a Data frame or a Multipurpose frame at the local MAC sublayer entity that passes the appropriate message filtering operations as described in 6.6.2. If the primitive is received while the device is in promiscuous mode, the parameters will be set as specified in 10.23.

8.3.7 MCPS-PURGE.request

The MCPS-PURGE.request primitive allows the next higher layer to purge an MSDU from the transaction queue.

The semantics of this primitive are as follows:

```
MCPS-PURGE.request      (
    MsduHandle
)
```

The primitive parameters are defined in Table 8-33.

Table 8-33—MCPS-PURGE.request parameters

Name	Type	Valid range	Description
MsduHandle	Integer	0x00–0xff	The handle of the MSDU to be purged from the transaction queue.

On receipt of the MCPS-PURGE.request primitive, the MAC sublayer attempts to find in its transaction queue the MSDU indicated by the msduHandle parameter. If an MSDU has left the transaction queue, the handle will not be found, and the MSDU can no longer be purged. If an MSDU matching the given handle is found, the MSDU is discarded from the transaction queue.

8.3.8 MCPS-PURGE.confirm

The MCPS-PURGE.confirm primitive allows the MAC sublayer to notify the next higher layer of the success of its request to purge an MSDU from the transaction queue.

The semantics of this primitive are as follows:

```
MCPS-PURGE.confirm      (
    MsduHandle,
    Status
)
```

The primitive parameters are defined in Table 8-34.

Table 8-34—MCPS-PURGE.confirm parameters

Name	Type	Valid range	Description
MsduHandle	Integer	0x00–0xff	The handle of the MSDU requested to be purged from the transaction queue.
Status	Enumeration	SUCCESS, INVALID_HANDLE	The status of the request to purge an MSDU from the transaction queue.

The MCPS-PURGE.confirm primitive is generated by the MAC sublayer entity in response to an MCPS-PURGE.request primitive. If an MSDU matching the given handle is found, the Status will be set to SUCCESS. If an MSDU matching the given handle is not found, the Status will be set to INVALID_HANDLE.

8.4 MAC constants and PIB attributes

8.4.1 General

This subclause specifies the constants and attributes required by the MAC sublayer.

8.4.2 MAC constants

The constants that define the characteristics of the MAC sublayer are presented in Table 8-35.

Table 8-35—MAC sublayer constants

Constant	Description	Value
<i>aBaseSlotDuration</i>	The number of symbols forming a superframe slot when <i>the superframe order</i> is equal to zero, as described in 10.2.	60
<i>aBaseSuperframeDuration</i>	The number of symbols forming a superframe when <i>the superframe order</i> is equal to zero.	<i>aBaseSlotDuration</i> × <i>aNumSuperframeSlots</i>
<i>aMaxLostBeacons</i>	The number of consecutive lost beacons that will cause the MAC sublayer of a receiving device to declare a loss of synchronization.	4

Table 8-35—MAC sublayer constants (continued)

Constant	Description	Value
<i>aMaxSifsFrameSize</i>	The maximum size of an MPDU, in octets, that can be followed by a SIFS period.	18
<i>aMinCapLength</i>	The minimum number of symbols forming the CAP. An exception to this minimum shall be allowed for the accommodation of the temporary increase in the beacon frame length needed to perform GTS maintenance, as described in 7.3.1.5. Additional restrictions apply when PCA is enabled, as described in 10.10.2.1.	440
<i>aNumSuperframeSlots</i>	The number of slots contained in any superframe.	16

8.4.3 MAC PIB attributes

8.4.3.1 Overview

The MAC PIB includes the attributes required to manage the MAC sublayer of a device. The attributes contained in the MAC PIB are presented in Table 8-36, Table 8-37, Table 8-38, and Table 8-39. Attributes marked with a dagger (\dagger) are read-only attributes (i.e., attribute can only be set by the MAC sublayer), which can be read by the next higher layer using the MLME-GET.request primitive. All other attributes can be read or written by the next higher layer using the MLME-GET.request or MLME-SET.request primitives, respectively. Attributes marked with an asterisk (*) are optional.

Table 8-36—MAC PIB attributes

Attribute	Type	Range	Description	Default
<i>macAoaEnable</i>	Boolean	TRUE, FALSE	Where AOA is supported by the PHY receiver this will enable/disable the measurement of AOA for received frames. Where AOA measurement is not needed for every frame some power saving may be made by disabling AOA measurement via this attribute.	FALSE
<i>macAutoRequest</i>	Boolean	TRUE, FALSE	Indication of whether a device automatically sends a Data Request command if its address is listed in the beacon frame. A value of TRUE indicates that the Data Request command is automatically sent. This attribute also affects the generation of the MLME-BEACON-NOTIFY.indication primitive, as described in 8.2.4.3.	TRUE

Table 8-36—MAC PIB attributes (continued)

Attribute	Type	Range	Description	Default
<i>macBattLifeExt</i>	Boolean	TRUE, FALSE	Indication of whether BLE, through the reduction of coordinator receiver operation time during the CAP, is enabled. A value of TRUE indicates that it is enabled. The effect of this attribute on the backoff exponent in the CSMA-CA algorithm is described in 6.3.2.1.	FALSE
<i>macBattLifeExtPeriods</i>	Integer	6–41	In BLE mode, the number of backoff periods during which the receiver is enabled after the IFS following a beacon. This value is dependent on the supported PHY and is the sum of three terms: Term 1: The value $2^x - 1$, where x is the maximum value of <i>macMinBe</i> in BLE mode (equal to two). This term is thus equal to three backoff periods. Term 2: The duration of the initial contention window length, as described in 6.3.2.1. Term 3: The Preamble field length and the SFD field length of the supported PHY summed together and rounded up (if necessary) to an integer number of backoff periods.	Dependent on currently selected PHY.
<i>macBeaconOrder</i>	Integer*	0–15	Indicates the frequency with which the beacon is transmitted, as defined in 10.2.	15
<i>macBeaconPayload</i>	Set of octets*	—	A sequence of zero or more octets to be transmitted in the Beacon Payload field.	NULL
<i>macBsn</i>	Integer*	0x00–0xff	The sequence number added to the transmitted beacon frame.	Random value from within the range
<i>macCoordExtendedAddress</i>	IEEE address	An extended IEEE address	The address of the coordinator through which the device is associated.	—
<i>macCoordShortAddress</i>	Integer	0x0000–0xffff	The short address assigned to the coordinator through which the device is associated. A value of 0xffffe indicates that the coordinator is only using its extended address. A value of 0xfffff indicates that this value is unknown.	0xfffff
<i>macDsn</i>	Integer	0x00–0xff	The sequence number added to the transmitted Data frame or MAC command.	Random value from within the range

Table 8-36—MAC PIB attributes (continued)

Attribute	Type	Range	Description	Default
<i>macExtendedAddress</i>	IEEE address†	Device specific	The extended address assigned to the device.	—
<i>macFcsType</i>	Integer	0–1	The type of the FCS, as defined in 7.2.11. A value of zero indicates a 4-octet FCS. A value of one indicates a 2-octet FCS. This attribute is only valid for LECIM, TVWS, SUN PHYs, and the HRP UWB PHY in HPRF mode.	0
<i>macGroupRxMode</i>	Boolean	TRUE, FALSE	Enables the reception of 64-bit group addresses.	FALSE
<i>macGtsPermit</i>	Boolean*	TRUE, FALSE	TRUE if the PAN coordinator is to accept GTS requests. FALSE otherwise.	TRUE
<i>macImplicitBroadcast</i>	Boolean	TRUE, FALSE	Indicates whether frames without a destination PAN ID and a destination address are to be treated as though they are addressed to the broadcast PAN ID and broadcast short address.	FALSE
<i>macLifsPeriod</i>	Integer†	As defined in 11.1.4	The minimum time forming a LIFS period.	PHY dependent
<i>macMaxBe</i>	Integer	3–8	The maximum value of the backoff exponent, BE, in the CSMA-CA algorithm, as defined in 6.3.2.1.	5
<i>macMaxCsmaBackoffs</i>	Integer	0–5	The maximum number of backoffs the CSMA-CA algorithm will attempt before declaring a channel access failure.	4
<i>macMaxFrameRetries</i>	Integer	0–7	The maximum number of retries allowed after a transmission failure.	3
<i>macNotifyAllBeacons</i>	Boolean	TRUE, FALSE	If TRUE, all Beacon frames that have a Status of SUCCESS from the unsecuring process will be notified to the next higher layer. If FALSE, only tracking Beacon frames with a Status of SUCCESS from the unsecuring process will be notified to the next higher layer, as described in 10.2.6.	FALSE
<i>macMinBe</i>	Integer	0– <i>macMaxBe</i>	The minimum value of the backoff exponent (BE) in the CSMA-CA algorithm, as described in 6.3.2.1.	3

Table 8-36—MAC PIB attributes (continued)

Attribute	Type	Range	Description	Default
<i>macPanId</i>	Integer	0x0000–0xffff	The identifier of the PAN on which the device is operating. If this value is 0xffff, the device is not associated.	0xffff
<i>macResponseWaitTime</i>	Integer	2–64	The maximum time, in multiples of <i>aBaseSuperframeDuration</i> , a device shall wait for a response command to be available following a request command.	32
<i>macRxOnWhenIdle</i>	Boolean	TRUE, FALSE	Indication of whether the MAC sublayer is to enable its receiver during idle periods. For a PAN using superframe structure, this attribute is relevant only during the CAP of the incoming superframe. For a PAN not using superframe structure, this attribute is relevant at all times.	FALSE
<i>macSecurityEnabled</i>	Boolean	TRUE, FALSE	Indication of whether the MAC sublayer has security enabled. A value of TRUE indicates that security is enabled, while a value of FALSE indicates that security is disabled.	FALSE
<i>macShortAddress</i>	Integer	0x0000–0xffff	The address that the device uses to communicate in the PAN. If the device is the PAN coordinator, this value shall be chosen before a PAN is started. Otherwise, the short address is allocated by a coordinator during association.	0xffff
<i>macSifsPeriod</i>	Integer†	As defined in 11.1.4	The minimum time forming a SIFS period.	PHY dependent
<i>macSyncSymbolOffset</i>	Integer†	0x000–0x100 for the 2.4 GHz band, 0x000–0x400 for the 868 MHz and 915 MHz bands, and the SUN FSK and SUN OFDM PHYs	The offset, measured in symbols, between the symbol boundary at which the MLME captures the timestamp of each transmitted or received frame, and the onset of the first symbol past the SFD.	—
<i>macTimestampSupported</i>	Boolean†	TRUE, FALSE	Indication of whether the MAC sublayer supports the optional timestamping feature for incoming and outgoing Data frames.	—

Table 8-36—MAC PIB attributes (continued)

Attribute	Type	Range	Description	Default
<i>macTransactionPersistenceTime</i>	Integer*	0x0000–0xffff	The maximum time (in unit periods) that a transaction is stored by a coordinator and indicated in its beacon. The unit period is governed by <i>macBeaconOrder</i> , <i>BO</i> , as follows: For $0 \leq BO \leq 14$, the unit period will be $aBaseSuperframeDuration \times 2^{BO}$. For $BO = 15$, the unit period will be <i>aBaseSuperframeDuration</i> .	0x01f4
<i>macUnitBackoffPeriod</i>	Integer	PHY specific	The number of symbols forming the basic time period used by the CSMA-CA algorithm. The <i>phyCcaDuration</i> in the default is rounded up to the next integer number of symbol periods using the ceiling() function before addition to the <i>aTurnaroundTime</i> . ^a	<i>aTurnaroundTime</i> + <i>phyCcaDuration</i> .

^a The function ceiling() returns the smallest integer value greater than or equal to its argument value.

8.4.3.2 General MAC PIB attributes for functional organization

Table 8-37 provides the General MAC PIB attributes for functional organization. Attributes marked with a dagger (†) are read-only attributes (i.e., attribute may only be set by the MAC sublayer), which can be read by the next higher layer using the MLME-GET.request primitive. All other attributes can be read or written by the next higher layer using the MLME-GET.request or MLME-SET.request primitives, respectively.

Table 8-37—General MAC PIB attributes for functional organization

Attribute	Type	Range	Description	Default
<i>macDsmeCapable</i>	Boolean†	TRUE, FALSE	If TRUE, the device is capable of functionality specific to DSME as described in 10.4.	—
<i>macDsmeEnabled</i>	Boolean	TRUE, FALSE	If TRUE, the device is using functionality specific to DSME.	—
<i>macDaCapable</i>	Boolean†	TRUE, FALSE	If TRUE, the device is capable of functionality specific to DA as described in 10.24.	—
<i>macDaEnabled</i>	Boolean	TRUE, FALSE	If TRUE, the device is using functionality specific to DA.	—
<i>macExtendedDsmeCapable</i>	Boolean†	TRUE, FALSE	A value of TRUE indicates that the device is capable of functionality specific to ExtendedDSME.	—
<i>macExtendedDsmeEnabled</i>	Boolean	TRUE, FALSE	A value of TRUE indicates that the device is using functionality specific to ExtendedDSME.	FALSE

Table 8-37—General MAC PIB attributes for functional organization (continued)

Attribute	Type	Range	Description	Default
<i>macHoppingCapable</i>	Boolean†	TRUE, FALSE	If TRUE, the device is capable of unslotted channel hopping as described in 10.16.	—
<i>macHoppingEnabled</i>	Boolean	TRUE, FALSE	If TRUE, the device is using unslotted channel hopping.	—
<i>macLeCapable</i>	Boolean†	TRUE, FALSE	If TRUE, the device is capable of functionality specific to low energy as described in 10.5.	—
<i>macLeEnabled</i>	Boolean	TRUE, FALSE	If TRUE, the device is using functionality specific to low energy.	—
<i>macLeHsEnabled</i>	Boolean	TRUE, FALSE	A value of TRUE indicates that the device is using functionality specific to low-energy handshake.	—
<i>macMetricsCapable</i>	Boolean†	TRUE, FALSE	If TRUE, the device is capable of providing additional MAC metrics as described in 10.27.	—
<i>macMetricsEnabled</i>	Boolean	TRUE, FALSE	If TRUE, the device is providing additional MAC metrics.	—
<i>macRccnCapable</i>	Boolean†	TRUE, FALSE	If TRUE, the device is capable of functionality specific to RCCN as described in 10.13.	—
<i>macRccnEnabled</i>	Boolean	TRUE, FALSE	If TRUE, the device is using functionality specific to an RCCN.	—
<i>macSrmCapable</i>	Boolean†	TRUE FALSE	If TRUE, the device is capable of functionality specific to SRM as described in 10.28.	—
<i>macSrmEnabled</i>	Boolean	TRUE FALSE	If TRUE, the device is using functionality specific to SRM	—
<i>macTrleCapable</i>	Boolean†	TRUE FALSE	If TRUE, the device is capable of functionality specific to TRLE as described in 10.37.	—
<i>macTrleEnabled</i>	Boolean	TRUE, FALSE	If TRUE, the device is using functionality specific to TRLE.	—
<i>macTrleRelayingMode</i>	Boolean	TRUE, FALSE	If TRUE, the device is using TRLE relaying mode, as defined in 10.37.3.	—
<i>macTschCapable</i>	Boolean†	TRUE, FALSE	If TRUE, the device is capable of functionality specific to TSCH as described in 10.3.	—
<i>macTschEnabled</i>	Boolean	TRUE, FALSE	If TRUE, the device is using functionality specific to TSCH.	—

8.4.3.3 Enhanced Beacon Request command specific MAC PIB attributes

Enhanced Beacon Request command specific attributes are described in Table 8-38.

Table 8-38—Enhanced Beacon Request command specific MAC PIB attributes

Attribute	Type	Range	Description	Default
<i>macBeaconAutoRespond</i>	Boolean	TRUE, FALSE	When TRUE, device responds to beacon requests and enhanced beacon requests automatically. When FALSE, device passes beacon/enhanced beacon payload up to higher layer using MLME-BEACONREQUEST.indication.	TRUE
<i>macEbrAttributeList</i>	List of attribute identifiers	0x00–0xff	Contains attribute identifiers, as defined in Table 6-1.	—
<i>macEbrFilters</i>	List of Booleans		Contains which Enhanced Beacon Request command filter field bits should be set.	—
<i>macEbrLinkQuality</i>	Integer	0x00–0xff	Link quality level to be transmitted in the Enhanced Beacon Request command.	—
<i>macEbrPercentFilter</i>	Integer	0–100	Percent filter threshold value to be transmitted in the Enhanced Beacon Request command.	—
<i>macEbrPermitJoining</i>	Boolean	TRUE, FALSE	When TRUE, the Permit Joining request will be included in the Enhanced Beacon Request command.	—

8.4.3.4 Enhanced Beacon frame specific MAC PIB attributes

Enhanced Beacon frame specific attributes are described in Table 8-39.

Table 8-39—Enhanced Beacon frame specific MAC PIB attributes

Attribute	Type	Range	Description	Default
<i>macEbAutoSa</i>	Enumeration	NONE, SHORT, FULL	Indicates if Enhanced Beacon frames generated by the MAC in response to an Enhanced Beacon Request command include Source Address field.	FULL
<i>macEbFilteringEnabled</i>	Boolean	TRUE, FALSE	Indicates if devices should perform filtering in response to Enhanced Beacon Request command.	—
<i>macEbHeaderIeList</i>	List of Header IEs	As defined in 7.4	A list of Header IEs to include in the enhanced beacon.	—
<i>macEbPayloadIeList</i>	List of Payload IEs	As defined in 7.4	A list of Payload IEs to include in the enhanced beacon.	—

Table 8-39—Enhanced Beacon frame specific MAC PIB attributes (continued)

Attribute	Type	Range	Description	Default
<i>macEbsn</i>	Integer	0x00–0xff	BSN used for Enhanced Beacon frames.	—
<i>macUseEnhancedBeacon</i>	Boolean	TRUE, FALSE	When TRUE, in a PAN using superframe structure, the device should use Enhanced Beacons rather than standard beacons.	—

9. Security

9.1 Overview

The MAC sublayer is responsible for providing security services on specified incoming and outgoing frames when requested to do so by the higher layers. This standard supports the following security services:

- DATA confidentiality
- Data authenticity
- Replay protection (when not using TSCH mode)

When TSCH mode is enabled, the nonce is generated again for each retransmission, thus the receiving device has no way of distinguishing whether the frame is a retransmission or not from the absolute slot number (ASN). Thus full replay protection in TSCH mode is not provided. When TSCH mode is enabled, devices shall use only one security level per key. For additional details, see B.3.4.

9.2 Functional description

9.2.1 General

A device may optionally implement security. A device that implements security shall provide a mechanism for the MAC sublayer to perform cryptographic transformations on incoming and outgoing frames using information in the PIB attributes associated with security only if the *macSecurityEnabled* attribute is set to TRUE. A device that does not implement security is not required to provide a mechanism for the MAC sublayer to perform any cryptographic transformation on incoming and outgoing frames nor require any PIB attributes associated with security.

Security specific MAC PIB values are italicized and have a prefix of *sec*, for example *secFrameCounter*.

Informative diagrams of the various security state machines can be found in Kivinen [B20].

9.2.2 Outgoing frame security procedure

The inputs to this procedure are the frame to be secured and the SecurityLevel, KeyIdMode, KeySource, and KeyIndex elements inside *SecurityParameterDescriptor*. The MLME-START.request primitive gives SecurityParamameterDescriptors for Beacon frames and Coordinator Realignment commands. If the frame was generated in response to an MLME or MCPS primitive, then the SecurityLevel, KeyIdMode, KeySource, and KeyIndex elements inside *SecurityParameterDescriptor* corresponding the primitive are used. Otherwise, the inputs are as follows:

- When transmitting Enhanced Beacons the *SecurityParameterDescriptor* of *secEnhancedBeaconSecurityParams* is used.
- Otherwise *SecurityParameterDescriptor* of *secAutoRequestSecurityParams* is used.

The outputs from this procedure are the Status of the procedure and, if this Status is SUCCESS, the secured frame.

This procedure involves the following steps:

- a) **Is security needed?** If the SecurityLevel parameter is zero, the procedure shall set the secured frame to be the frame to be secured and return with a Status of SUCCESS.
- b) **Is security enabled?** If *macSecurityEnabled* is set to FALSE, the procedure shall return with a Status of UNSUPPORTED_SECURITY.
- c) **Obtain KeyDescriptor.** The procedure shall obtain the KeyDescriptor using the KeyDescriptor lookup procedure as described in 9.2.3 using the KeyIdMode, KeyIndex, and KeySource with the DeviceAddressingMode set to Destination Addressing Mode field, DevicePanId set to the Destination PAN ID field, and DeviceAddress set to the Destination Address field. If that procedure fails, the procedure shall return with a Status of UNAVAILABLE_KEY.
- d) **Check frame counter value.**
 - 1) If TSCH mode is not being used and the *secFrameCounterPerKey* in the KeyDescriptor is set to FALSE and *secFrameCounter* has the value 0xffffffff, the procedure shall return with a Status of COUNTER_ERROR.
 - 2) If TSCH mode is not being used and the *secFrameCounterPerKey* in the KeyDescriptor is set to TRUE and *secKeyFrameCounter* element of the KeyDescriptor has the value 0xffffffff, the procedure shall return with a Status of COUNTER_ERROR.
- e) **Insert Auxiliary Security Header field.** The procedure shall insert the Auxiliary Security Header field in the frame to be secured, with the fields set as follows:
 - 1) The Security Level field of the Security Control field shall be set to the SecurityLevel parameter.
 - 2) The Key Identifier Mode field of the Security Control field shall be set to the KeyIdMode parameter.
 - 3) If TSCH mode is being used, the Frame Counter Suppression field in the Security Control field shall be set to one. Otherwise, the Frame Counter Suppression field in the Security Control field shall be set to zero.
 - 4) The Frame Counter field shall be set as follows:
 - i) If TSCH mode is being used, the Frame Counter field shall be omitted.
 - ii) If the *secFrameCounterPerKey* in the KeyDescriptor is set to TRUE, the Frame Counter field shall be set to *secKeyFrameCounter*.
 - iii) Otherwise, the Frame Counter field shall be set to *secFrameCounter*.
 - 5) If the KeyIdMode parameter is set to a value not equal to zero, the Key Source and Key Index fields of the Key Identifier field shall be set to the KeySource and KeyIndex parameters, respectively.
- f) **Secure the frame.** For the frames specified in Table 9-1, the Private Payload field and Open Payload field shall be set as indicated in the table. For frames not specified in Table 9-1, the Private Payload shall be set to the MAC Payload field, and the Open Payload field shall be empty. If the algorithm specified by *secAeadAlgorithm* is not supported, then the procedure shall return with a Status of UNSUPPORTED_ALGORITHM. If the size of *secKey* does not match the key length requirements of the algorithm specified by *secAeadAlgorithm*, then the procedure shall return with a Status of KEY_LENGTH_MISMATCH. The procedure shall then use the Private Payload field, the Open Payload field, the *macExtendedAddress*, the Frame Counter field (if TSCH is not being used), the ASN (if TSCH is being used), the SecurityLevel parameter, and the *secKey* and *secAeadAlgorithm* elements of the KeyDescriptor to produce the secured frame according to the transformation process defined in 9.3.4.

Table 9-1—Exceptions to Private Payload field and Open Payload field definitions

Frame type	Private Payload field	Open Payload field
Beacon (Frame Version < 2)	Beacon Payload field	All other fields in the MAC Payload field
MAC Command (Frame Version < 2)	Content field	Command ID field

- g) **Store frame counter.**
 - 1) If not using TSCH mode and *secFrameCounterPerKey* in the KeyDescriptor is set to TRUE, the procedure shall increment *secKeyFrameCounter* element of the KeyDescriptor by one.
 - 2) If not using TSCH mode and *secFrameCounterPerKey* in the KeyDescriptor is set to FALSE, the procedure shall increment *secFrameCounter* by one.
- h) **Finish procedure.** The procedure shall return with a Status of SUCCESS.

9.2.3 KeyDescriptor lookup procedure

The inputs to this procedure are the KeyIdMode, KeySource, KeyIndex, DeviceAddressingMode, DevicePanId, and DeviceAddress. The outputs from this procedure are a Status and, if Status is set to SUCCESS, a KeyDescriptor.

This procedure involves the following steps:

- a) If the KeyIdMode parameter is set to 0x00, then for each *secKeyIdLookupDescriptor* with *secKeyIdMode* set to 0x00 in the *secKeyIdLookupList*:
 - 1) If the DeviceAddressingMode is set to NONE or if the DevicePanId is not set, then the DevicePanId shall be set to *macPanId*.
 - 2) If the DeviceAddressingMode is set to NONE and the frame type is beacon, then the DeviceAddress shall be *macCoordExtendedAddress*.
 - 3) If the DeviceAddressingMode is set to NONE and the frame type is not beacon, then:
 - i) If the *macCoordShortAddress* attribute is set to 0xffff, then the DeviceAddress shall be set to the *macCoordExtendedAddress*.
 - ii) If the *macCoordShortAddress* attribute is set to a value of 0x0000–0xffffd, then the DeviceAddress shall be set to the *macCoordShortAddress*.
 - iii) If the *macCoordShortAddress* attribute is set to 0xfffff, the procedure shall return with Status set to FAILED.
 - 4) If the DeviceAddressingMode, DevicePanId, and DeviceAddress match the *secKeyDeviceAddrMode*, *secKeyDevicePanId*, and *secKeyDeviceAddress*, respectively, of a *secKeyIdLookupDescriptor*, then the procedure returns with the corresponding *secKeyItem* and Status set to SUCCESS.
- b) If the KeyIdMode parameter is set to 0x01 and KeyIndex matches the *secKeyIndex* of a *secKeyIdLookupDescriptor* that has *secKeyIdMode* set to 0x01, then the procedure returns with the KeyDescriptor set to the corresponding *secKeyItem* and Status set to SUCCESS.
- c) If the KeyIdMode parameter is set to 0x02 or 0x03 and KeySource, KeyIdMode, and KeyIndex match *secKeySource*, *secKeyIdMode*, and *secKeyIndex*, respectively, of a *secKeyIdLookupDescriptor*, then the procedure returns with the KeyDescriptor set to the corresponding *secKeyItem* and Status set to SUCCESS.
- d) The procedure shall return with Status set to FAILED.

NOTE—For broadcast frames, the KeyDescriptor lookup procedure will result in Status set to FAILED if implicit key identification is used. Hence, explicit key identification should be used for broadcast frames.

9.2.4 Incoming frame security procedure, Security Enabled field is set to one

This procedure shall only be used for incoming frames in which the Security Enabled field is set to one. For frames in which the Security Enabled field is set to zero, the procedure in 9.2.5 is used instead.

The input to this procedure is the frame to be unsecured. The outputs from this procedure are the status of the procedure, the unsecured frame (including all IEs), IeStatusList, and *SecurityParameterDescriptor* containing SecurityLevel, KeyIdentifierMode, KeySource, and KeyIndex elements. The status for an IE in the IeStatusList is set to PASSED if the IE conforms to the security policy for that IE and is set to FAILED otherwise.

All outputs of this procedure are assumed to be invalid unless and until explicitly set in this procedure.

This procedure involves the following steps:

- Legacy security.** If the Frame Version field of the frame to be unsecured is set to zero, the procedure shall return with a Status of UNSUPPORTED_LEGACY.
- Check for *macSecurityEnabled*.** If *macSecurityEnabled* is set to FALSE, the procedure shall return with a Status of UNSUPPORTED_SECURITY.
- Parse Auxiliary Security Header field.** The procedure shall set SecurityLevel and KeyIdentifierMode to the Security Level field and Key Identifier Mode field, respectively, of the frame to be unsecured. If required by the KeyIdentifierMode, the KeySource and KeyIndex shall be set to the Key Source field and Key Index field, respectively, of the Key Identifier field of the frame to be unsecured. If the resulting SecurityLevel is zero, the procedure shall return with a Status of UNSUPPORTED_SECURITY.
- Obtain source address.** DevicePanId shall be set to the Source PAN ID field, if it is present. Otherwise, DevicePanId shall be set to the Destination PAN ID field, if present. If neither PAN ID field is present, then DevicePanId shall be set to *macPanId*. The DeviceAddressingMode shall be set based on the Source Addressing Mode field using the mapping in Table 9-2. The DeviceAddress shall be set to the Source Address field, if present.

Table 9-2—Mapping of Source Addressing Mode field to DeviceAddressingMode

Source Addressing Mode field	DeviceAddressingMode
0x00	NONE
0x02	SHORT
0x03	EXTENDED

- Obtain KeyDescriptor.** The procedure shall obtain the KeyDescriptor using the KeyDescriptor lookup procedure as described in 9.2.3 using the KeyIdMode, KeyIndex, KeySource, DeviceAddressingMode, DevicePanId, and DeviceAddress. If the KeyDescriptor lookup procedure fails, the procedure shall return with a Status of UNAVAILABLE_KEY.
- Obtain DeviceDescriptor.** The procedure shall obtain the DeviceDescriptor using the DeviceDescriptor lookup procedure described in 9.2.6 using the DeviceAddressingMode, DevicePanId, and DeviceAddress. If that procedure fails, then the procedure shall return with a Status of UNAVAILABLE_DEVICE.

- g) **Obtain frame counter.** If TSCH mode is being used, then this step is skipped.
 - 1) If *secFrameCounterPerKey* of the KeyDescriptor is FALSE, the FrameCounterCheck value shall be set to be the *secDeviceMinFrameCounter* element of the DeviceDescriptor.
 - 2) If *secFrameCounterPerKey* of the KeyDescriptor is TRUE and there is a *secKeyDeviceFrameCounterDescriptor* in the *secKeyDeviceFrameCounterList* in which *secDeviceExtAddress* matches *secExtAddress* of the DeviceDescriptor, then the procedure shall set the FrameCounterCheck value to the *secDeviceFrameCounter* of that *secKeyDeviceFrameCounterDescriptor*.
 - 3) Otherwise, the FrameCounterCheck value is set to zero.
- h) **Check frame counter.** If TSCH mode is being used, then this step is skipped. If the Frame Counter field of the frame to be unsecured has the value 0xffffffff or the Frame Counter field of the frame to be unsecured is less than the FrameCounterCheck value, the procedure shall return with a Status of COUNTER_ERROR.
- i) **Unsecure frame.** For frames specified in Table 9-1, the Private Payload field and Open Payload field shall be set as indicated in the table. Otherwise, the Private Payload field shall be set to the MAC payload field and the Open Payload field shall be empty. If the algorithm specified by *secAeadAlgorithm* is not supported, then the procedure shall return with a Status of UNSUPPORTED_ALGORITHM. If the size of *secKey* does not match the key length requirements of the algorithm specified by *secAeadAlgorithm*, then the procedure shall return with a Status of KEY_LENGTH_MISMATCH. The procedure shall then use the Private Payload field, the Open Payload field, *secExtAddress* of the DeviceDescriptor, the Frame Counter field of the frame to be unsecured (if TSCH is not being used), the ASN (if TSCH is being used), SecurityLevel, and the *secKey* and *secAeadAlgorithm* elements of the KeyDescriptor to produce the unsecured frame, according to the inverse transformation process described in the security operations, as described in 9.3.5. If the inverse transformation process fails, the procedure shall return with a Status of SECURITY_ERROR.
- j) **Store frame counter.** If not using TSCH mode and *secFrameCounterPerKey* of the KeyDescriptor is FALSE, then *secDeviceMinFrameCounter* of the *secDeviceDescriptor* shall be set to the value of the Frame Counter plus one. If not using TSCH mode and *secFrameCounterPerKey* of the KeyDescriptor is TRUE, then *secDeviceFrameCounter* of the *secKeyDeviceFrameCounterDescriptor* corresponding to *secExtAddress* shall be set to the value of Frame Counter plus one. If the *secKeyDeviceFrameCounterDescriptor* does not exist it shall be created by setting *secDeviceExtAddress* and *secDeviceFrameCounter* to *secExtAddress*, and Frame Counter plus one, respectively. The newly created *secKeyDeviceFrameCounterDescriptor* shall be added to *secKeyDeviceFrameCounterList*.
- k) **Obtain SecurityLevelDescriptor.** The procedure shall obtain the SecurityLevelDescriptor by passing the Frame Type field and, if the frame is a MAC command, the Command ID field, of the frame to be unsecured to the SecurityLevelDescriptor lookup procedure described in 9.2.7. If that procedure fails, the procedure shall return with a Status of UNAVAILABLE_SECURITY_LEVEL.
- l) **Check IE security.** If the IE present field of the frame to be unsecured is set to one, the procedure shall determine whether the IEs in the frame to be unsecured conform to the security level policy by passing the IEs from the frame, DeviceDescriptor, SecurityLevelDescriptor, and the SecurityLevel to the incoming IE security level checking procedure, as described in 9.2.8.
- m) **Check IE Key Usage Policy.** If the IE present field of the frame to be unsecured is set to one, the procedure shall determine whether the frame to be unsecured conforms to the key usage policy by passing the IeStatusList, KeyDescriptor, the IEs from the frame, the Frame Type field, and, if the frame is a MAC command, the Command ID field, to the incoming IE key usage policy checking procedure, as described in 9.2.9.
- n) **Check security level.** The procedure shall determine whether the frame to be unsecured conforms to the security level policy by passing the SecurityLevelDescriptor and the SecurityLevel to the incoming security level checking procedure, as described in 9.2.10. If that procedure returns with a

Status of FAILED, the procedure shall return with the IEs from the unsecured frame, the IeStatusList, and a Status of IMPROPER_SECURITY_LEVEL.

- o) **Check key usage policy.** The procedure shall determine whether the frame to be unsecured conforms to the key usage policy by passing the KeyDescriptor, the Frame Type field, and, if the frame is a MAC command, the Command ID field, to the incoming key usage policy checking procedure, as described in 9.2.11. If that procedure fails, the procedure shall return with the IEs from the unsecured frame, the IeStatusList, and a Status of IMPROPER_KEY_TYPE.
- p) **Return unsecured frame.** The procedure shall return with the unsecured frame, *SecurityParameterDescriptor* containing SecurityLevel, KeyIdentifierMode, KeySource, and KeyIndex elements, IeStatusList, and a Status of SUCCESS.

9.2.5 Incoming frame security procedure, Security Enabled field is set to zero

This procedure shall only be used for incoming frames in which the Security Enabled field is set to zero. For frames in which the Security Level field is set to one, the procedure in 9.2.4 is used instead.

The input to this procedure is the frame to be validated. The outputs from this procedure are the status of the procedure, the validated frame (including all IEs), and IeStatusList. The status for an IE in the IeStatusList is set to PASSED if the IE conforms to the security policy for that IE and is set to FAILED otherwise.

All outputs of this procedure are assumed to be invalid unless and until explicitly set in this procedure.

This procedure involves the following steps:

- a) **Check for *macSecurityEnabled*.** If *macSecurityEnabled* is set to FALSE, the procedure shall set the validated frame to be the frame to be validated and return with a Status of SUCCESS.
- b) **Obtain source address.** DevicePanId shall be set to the Source PAN ID field, if it is present. Otherwise, DevicePanId shall be set to the Destination PAN ID field, if present. If neither PAN ID field is present, then DevicePanId shall be set to *macPanId*. DeviceAddressingMode shall be set to the Source Addressing Mode field. The DeviceAddress shall be set to the Source Address, if present.
- c) **Obtain DeviceDescriptor.** The procedure shall obtain the DeviceDescriptor using the DeviceDescriptor lookup procedure described in 9.2.6 using DeviceAddressingMode, DevicePanId, and DeviceAddress with the SecurityLevel set to zero. If that procedure fails, then the procedure shall return with a Status of UNAVAILABLE_DEVICE.
- d) **Obtain SecurityLevelDescriptor.** The procedure shall obtain the SecurityLevelDescriptor by passing the Frame Type field and, if the frame is a MAC command, the Command ID field, of the frame to be validated to the SecurityLevelDescriptor lookup procedure described in 9.2.7. If that procedure fails, the procedure shall return with a Status of UNAVAILABLE_SECURITY_LEVEL.
- e) **Check IE security.** If the IE present field of the frame to be validated is set to one, the procedure shall determine whether the IEs in the frame to be validated conform to the security level policy by passing the DeviceDescriptor, the SecurityLevelDescriptor, the SecurityLevel set to zero and the IEs from the frame to the incoming IE security level checking procedure, as described in 9.2.8. That procedure will return the IeStatusList.
- f) **Check security level.** The procedure shall determine whether the frame to be validated conforms to the security level policy by passing the SecurityLevelDescriptor and the SecurityLevel set to zero to the incoming security level checking procedure, as described in 9.2.10. If incoming security level checking procedure returns with a Status of FAILED, the procedure shall return with a Status of IMPROPER_SECURITY_LEVEL. If the incoming security level checking procedure returns with a Status of CONDITIONALLY_PASSED and the *secExempt* element of the DeviceDescriptor is set to FALSE, the procedure shall return with a status of IMPROPER_SECURITY_LEVEL.
- g) **Return frame.** The procedure shall set the validated frame to be the frame to be validated and return with the frame to be validated, IeStatusList, and a status of SUCCESS.

9.2.6 DeviceDescriptor lookup procedure

The inputs to this procedure are DeviceAddressingMode, the DevicePanId, and the DeviceAddress. The output from this procedure is a Status of either PASSED or FAILED, and, if PASSED, a DeviceDescriptor.

This procedure involves the following steps:

- a) If the DeviceAddressingMode is set to NONE, then the DevicePanId shall be set to *macPanId*.
- b) If the DeviceAddressingMode is set to NONE, then:
 - 1) If the *macCoordShortAddress* attribute is set to 0xffff, then the DeviceAddress shall be set to the *macCoordExtendedAddress*.
 - 2) If the *macCoordShortAddress* attribute is set to a value of 0x0000–0xffffd, then the DeviceAddress shall be set to the *macCoordShortAddress*.
 - 3) If the *macCoordShortAddress* attribute is set to 0xfffff, the procedure shall return with a Status set to FAILED.
- c) For each DeviceDescriptor in *secDeviceList*, if DevicePanId matches the *secPanId* and DeviceAddress matches *secShortAddress*, if the DeviceAddressingMode is set to SHORT, or the *secExtAddress*, if the DeviceAddressingMode is set to EXTENDED, then the procedure shall return with the corresponding DevicesDescriptor and Status set to PASSED.
- d) The procedure shall return with a Status set to FAILED.

9.2.7 SecurityLevelDescriptor lookup procedure

The inputs to this procedure are the Frame Type field and, if the frame is a MAC command, the Command ID field. The output from this procedure are a Status of either PASSED or FAILED, and, if PASSED, a SecurityLevelDescriptor.

This procedure involves the following steps:

- a) For each *secSecurityLevelDescriptor* in the *secSecurityLevelList* attribute:
 - 1) If the frame type indicates that the frame is not a MAC command and the Frame Type field is equal to the *secFrameType* element of the *secSecurityLevelDescriptor*, the procedure shall return with the *secSecurityLevelDescriptor* and Status set to PASSED.
 - 2) If the Frame Type field indicates that the frame is a MAC command and the Frame Type is equal to the *secFrameType* element of the *secSecurityLevelDescriptor* and the Command ID field is equal to the *secCommandId* element of the *secSecurityLevelDescriptor*, the procedure shall return with the *secSecurityLevelDescriptor* and Status set to PASSED.
- b) The procedure shall return with Status set to FAILED.

9.2.8 Incoming IE security level checking procedure

The inputs to this procedure are DeviceDescriptor, SecurityLevelDescriptor, SecurityLevel, and the IEs in the frame. The output from this procedure is an IeStatusList, in which each element in the list is set to either PASSED or FAILED for each IE.

A match is found if the *secIeType* of the *secIeSecurityLevelDescriptor* matches the type of the IE and the *secIeId* of the *secIeSecurityLevelDescriptor* entry matches the ID of the IE.

This procedure involves the following steps:

- a) If *secIeSecurityLevelDescriptorList* of the SecurityLevelDescriptor is empty, then set the IeStatus in the IeStatusList to PASSED for each IE in the frame, and return IeStatusList.
- b) Set the IeStatus in the IeStatusList to FAILED for each IE in the frame.
- c) For each IE in the frame and for each *secIeSecurityLevelDescriptor* in *secIeSecurityLevelDescriptorList*, if the IE matches the *secIeSecurityLevelDescriptor* entry, then:
 - 1) The procedure shall check whether the tuple formed by *secAeadAlgorithm* from the *secKeyDescriptor* and SecurityLevel from the incoming frame is equal to any of the elements of the *secIeAllowedSecurityLevels* of the *secIeSecurityLevelDescriptor*. If this check is successful, the procedure shall set the IeStatus in the IeStatusList for this IE to PASSED.
 - 2) If the SecurityLevel is equal to 0x00 and *secIeDeviceOverrideSecurityLevels* of the *secIeSecurityLevelDescriptor* is set to TRUE, and the *secExempt* of the DeviceDescriptor is set to TRUE, the procedure shall set the IeStatus in the IeStatusList for this IE to PASSED.
- d) Return IeStatusList.

9.2.9 Incoming IE key usage policy checking procedure

The inputs to this procedure are KeyDescriptor, IeStatusList, Frame Type field, the IEs in the frame, and, if the frame is a MAC command, the Command ID field. The output from this procedure is an IeStatusList, in which each element in the list is set to either PASSED or FAILED for each IE.

A match is found for an IE if the *secKeyIeType* of the *secKeyIeUsageDescriptor* matches the type of the IE and the *secKeyIeId* of the *secKeyIeUsageDescriptor* entry matches the ID of the IE.

This procedure involves the following steps:

- a) Find the *secKeyUsageDescriptor* entry from the *secKeyUsageList* of KeyDescriptor for which the Frame Type field matches *secKeyUsageFrameType* and, if the frame is a MAC command, the Command ID field matches *secKeyUsageCommandId*. If a matching *secKeyUsageDescriptor* entry was not found, or if the *secKeyIeUsageDescriptorList* is empty in the *secKeyUsageDescriptor* that was found, then return IeStatusList.
- b) For each IE in the frame, if the IE does not match any of the *secKeyIeUsageDescriptor* entries, then set the IeStatus in the IeStatusList for this IE to FAILED.
- c) Return IeStatusList.

9.2.10 Incoming security level checking procedure

The inputs to this procedure are SecurityLevelDescriptor and SecurityLevel. The output from this procedure is Status set to one of PASSED, FAILED, or CONDITIONALLY_PASSED.

The incoming security level checking procedure involves the following steps:

- a) If *secAllowedSecurityLevels* in SecurityLevelDescriptor is not empty, the procedure shall check whether the tuple formed by *secAeadAlgorithm* from the *secKeyDescriptor* and SecurityLevel from the incoming frame is equal to any of the elements of the *secAllowedSecurityLevels* of the SecurityLevelDescriptor. If this check is successful, the procedure shall return with Status set to PASSED.
- b) If SecurityLevel is equal to 0x00 and the *secDeviceOverrideSecurityLevels* element of the SecurityLevelDescriptor is set to TRUE, the procedure shall return with Status set to CONDITIONALLY_PASSED.

- c) The procedure shall return with Status set to FAILED.

9.2.11 Incoming key usage policy checking procedure

The inputs to this procedure are the KeyDescriptor, the Frame Type field, and the Command ID field. The output from this procedure is Status set to PASSED or FAILED.

The incoming key usage policy checking procedure involves the following steps:

- a) For each *secKeyUsageDescriptor* in the *secKeyUsageList* of the KeyDescriptor:
 - 1) If the Frame Type field indicates that the frame is not a MAC command and the Frame Type field is equal to the *secKeyUsageFrameType* element of the *secKeyUsageDescriptor*, the procedure shall return with Status set to PASSED.
 - 2) If the Frame Type field indicates that the frame is a MAC command, the Frame Type is equal to the *secKeyUsageFrameType* element of the *secKeyUsageDescriptor*, and the Command ID field is equal to the *secKeyUsageCommandId* element of the *secKeyUsageDescriptor*, the procedure shall return with Status set to PASSED.
- b) The procedure shall return with Status set to FAILED.

9.3 Security operations

9.3.1 Integer and octet representation

9.3.1.1 General

This subclause describes the integer and octet representation conventions for the authenticated encryption with associated data (AEAD).

9.3.1.2 Strings and string operations

A string is a sequence of symbols over a finite set, the length of which is the number of symbols it contains. The empty string is the string of length 0. The right-concatenation of two strings x and y (over the same alphabet) of length m and n , respectively (notation: $x \parallel y$), is the string z of length $m + n$ with x on its leftmost m symbols and with y on its rightmost n symbols. An octet is a string of symbols of length eight, where every symbol is in the finite set {0,1}. In the context of security operations, all octets are strings over the binary set {0,1}.

9.3.1.3 Integers, octets, and their representation

Integers are represented as a string of octets, where an octet is a string of symbols in the binary set {0,1}. Integers shall be represented as octet strings in most-significant-octet-first order. Octets shall be represented as bit strings of length eight in most-significant-bit-first order.

For example, the 32-bit integer 0x12345678 is represented as the string of octets {0x12, 0x34, 0x56, 0x78}, where the first octet is represented as the string of bits: {0,0,0,1,0,0,1,0}.

9.3.2 AEAD nonce

9.3.2.1 AEAD nonce for non-TSCH mode

The nonce for non-TSCH mode shall be formatted as shown in Figure 9-1, with the leftmost field in the figure defining the first octets and the rightmost field defining the last octet of the nonce.

Octets: 8	4	1
Source Address	Frame Counter	Nonce Security Level

Figure 9-1—Nonce for non-TSCH mode

The Source Address field shall be set to the extended address of the device originating the frame.

The Frame Counter field shall be set to the value of the respective field in the Auxiliary Security Header field, as defined in 9.4.

The Nonce Security Level field is an unsigned integer that shall be set to the value of the Security Level field of the Security Control field, as defined in 9.4.2.

The Source Address field, Frame Counter field, and Security Level field shall be represented as specified in 9.3.1.

9.3.2.2 AEAD nonce for TSCH mode

When TSCH mode is enabled, the nonce shall be formatted as shown in Figure 9-2.

Octets: 8	5
Source Address	ASN

Figure 9-2—Nonce in TSCH mode

The Source Address shall either be set to the extended address of the device originating the frame or shall be formatted as illustrated in Figure 9-3.

Octets: 3	1	2	2
IEEE 802.15 CID	0x00	PAN ID	Short Address

Figure 9-3—Source Address field for TSCH mode with short addressing

The IEEE 802.15 CID field contains the assigned value of the CID for IEEE Std 802.15, which is BA-55-EC.

The PAN ID field contains the PAN ID.

The Short Address field contains the short address of the device originating the frame.

NOTE—When using short addresses in the nonce, it is important that the coordinator assign unique short addresses.

The ASN shall be set to the ASN of the timeslot during which the frame is sent.

9.3.2.3 AEAD nonce for Fragment frames

The nonce for Fragment frames shall be formatted as shown in Figure 9-4, with the leftmost field in the figure defining the first octets and the rightmost field defining the last octet of the nonce.

Octets: 8	Bits: 0–25	26–31	32–35	36	37–39
Source Address	PSDU Counter	Fragment Number	Reserved	Fragment Indicator	Security Level

Figure 9-4—Nonce for Fragment frames

The Source Address field is defined in 9.3.2.1.

The Security Level field is defined in 9.3.2.1.

The PSDU Counter field shall be set to the value of the PSDU Counter field of the Fragment Sequence Context Description (FSCD) IE that was used to set up this fragment transaction.

The Fragment Number field shall be set to the value of the Fragment Number field of the Fragment packet, as defined in 23.3.4.

The Fragment Indicator field shall be set to one.

9.3.3 AEAD prerequisites

Securing a frame involves the use of the AEAD encryption and authentication transformation, as described in references within Table 9-9. Unsecuring a frame involves the use of the AEAD decryption and authentication checking transformation, as described in references within Table 9-9.

The length M of the Authentication field for the AEAD forward transformation and the AEAD inverse transformation is determined from Table 9-6, using the Security Level field of the Security Control field of the auxiliary security header of the frame.

9.3.4 AEAD transformation data representation

9.3.4.1 General

This subclause describes how the inputs and outputs of the AEAD forward transformation, as described in references within Table 9-9, are formed.

The inputs are as follows:

- Key
- Nonce
- a data
- m data

The output is c data.

9.3.4.2 Key and Nonce data inputs

The Key data for the AEAD forward transformation is passed by the outgoing frame security procedure described in 9.2.2. The Nonce data for the transformation is constructed as described in 9.3.2.

9.3.4.3 *a* data and *m* data

In the AEAD transformation process, the data fields shall be applied as in Table 9-3.

NOTE—The MHR contains the Auxiliary Security Header field, as defined in 7.2.

Table 9-3—*a* data and *m* data for all security levels

Security level	<i>a</i> data	<i>m</i> data
0	None	None
1	MHR Open Payload field Unsecured Private Payload field	None
2	MHR Open Payload field Unsecured Private Payload field	None
3	MHR Open Payload field Unsecured Private Payload field	None
4	—	
5	MHR Open Payload field	Unsecured Private Payload field
6	MHR Open Payload field	Unsecured Private Payload field
7	MHR Open Payload field	Unsecured Private Payload field

9.3.4.4 *c* data output

In the AEAD transformation process, the data fields that are applied, or right-concatenated and applied, represent octet strings.

The Private Payload field of the original unsecured frame shall be replaced by the right-concatenation of that field and the *c* field if data confidentiality is not provided and shall be replaced by the *c* field otherwise. The contents of the *c* data for each of the security levels is defined in Table 9-4.

Table 9-4—*c* data for all security levels

Security level	<i>c</i> data
0	None
1	MIC-32
2	MIC-64
3	MIC-128
4	—
5	Encrypted Private Payload field MIC-32
6	Encrypted Private Payload field MIC-64
7	Encrypted Private Payload field MIC-128

9.3.5 AEAD inverse transformation data representation

9.3.5.1 General

This subclause describes how the inputs and outputs of the AEAD inverse transformation, as described in B.3.3, are formed.

The inputs are as follows:

- Key
- Nonce
- c data
- a data

The output is m data.

9.3.5.2 Key and Nonce data inputs

The Key data for the AEAD inverse transformation is passed by the incoming frame security procedure described in 9.2.4. The Nonce data for the transformation is constructed as described in 9.3.2.

9.3.5.3 c data and a data

In the AEAD inverse transformation process, the data fields shall be applied as in Table 9-5.

Table 9-5— c data and a data for all security levels

Security level	c data	a data
0	None	None
1	MIC-32	MHR Open Payload field Private Payload field
2	MIC-64	MHR Open Payload field Private Payload field
3	MIC-128	MHR Open Payload field Private Payload field
4	—	—
5	Encrypted Private Payload field MIC-32	MHR Open Payload field
6	Encrypted Private Payload field MIC-64	MHR Open Payload field
7	Encrypted Private Payload field MIC-128	MHR Open Payload field

NOTE—The MHR contains the Auxiliary Security Header field, as defined in 7.2.

9.3.5.4 m data output

The Private Payload field of the MAC Payload shall be set to the m data if frame security includes providing confidentiality and shall be set to the Private Payload field of the MAC Payload, with the rightmost substring, c , deleted, otherwise.

9.4 Auxiliary security header

9.4.1 General

The Auxiliary Security Header field has a variable length and contains information required for security processing, including a Security Control field, a Frame Counter field, and a Key Identifier field. The Auxiliary Security Header field shall be present only if the Security Enabled field is set to one. The Auxiliary Security Header field shall be formatted as illustrated in Figure 9-5.

Octets: 1	0/4	0/1/5/9
Security Control	Frame Counter	Key Identifier

Figure 9-5—Format of the auxiliary security header

The auxiliary security header uses the representation conventions specified in 7.1.

9.4.2 Security Control field

9.4.2.1 General

The Security Control field is used to provide information about what protection is applied to the frame. The Security Control field shall be formatted as shown in Figure 9-6.

Bit: 0–2	3–4	5	6	7
Security Level	Key Identifier Mode	Frame Counter Suppression	ASN in Nonce	Reserved

Figure 9-6—Security Control field format

9.4.2.2 Security Level field

The Security Level field indicates the actual frame protection that is provided. This value can be adapted on a frame-by-frame basis and allows for varying levels of data authenticity (to allow minimization of security overhead in transmitted frames where required) and for optional data confidentiality. The cryptographic protection offered by the various security levels is shown in Table 9-6.

Table 9-6—Security levels available to the MAC sublayer

Security level	Security level field b2 b1 b0	Security attributes	Data confidentiality	Data authenticity	MIC length (octets)
0	000	None	OFF	NO	0
1	001	MIC-32	OFF	YES	4
2	010	MIC-64	OFF	YES	8
3	011	MIC-128	OFF	YES	16
4	100	Reserved			

Table 9-6—Security levels available to the MAC sublayer (continued)

Security level	Security level field b2 b1 b0	Security attributes	Data confidentiality	Data authenticity	MIC length (octets)
5	101	ENC-MIC-32	ON	YES	4
6	110	ENC-MIC-64	ON	YES	8
7	111	ENC-MIC-128	ON	YES	16

In a previous version of this standard, security level 4 was a level that provided only data confidentiality but without data authenticity. This security level is deprecated and shall not be used in implementations compliant with this standard. Devices that receive frames with security level 4 shall discard them, as described in 9.2.4. The counter mode encryption and cipher block chaining message authentication code (CCM) used allows trivial changes to the underlaying encrypted data unless data authenticity is provided, thus using data confidentiality only is not useful. In the case of TSCH mode, security level 4 allows higher security level frames to be downgraded to security level 4 frames.

Security levels can be ordered according to the corresponding cryptographic protection offered. Here, a first security level SEC1 is greater than or equal to a second security level SEC2 if and only if SEC1 offers at least the protection offered by SEC2, both with respect to data confidentiality and with respect to data authenticity. The statement “SEC1 is greater than or equal to SEC2” shall be evaluated as TRUE if both of the following conditions apply:

- a) Bit position b2 in SEC1 is greater than or equal to bit position b2 in SEC2 (where Encryption OFF < Encryption ON).
- b) The integer value of bit positions b1 b0 in SEC1 is greater than or equal to the integer value of bit positions b1 b0 in SEC2 (where increasing integer values indicate increasing levels of data authenticity provided, i.e., message integrity code MIC-0 < MIC-32 < MIC-64 < MIC-128).

Otherwise, the statement shall be evaluated as FALSE.

For example, $\text{ENC-MIC-64} \geq \text{MIC-64}$ is TRUE because ENC-MIC-64 offers the same data authenticity protection as MIC-64, plus confidentiality. On the other hand, $\text{MIC-128} \geq \text{ENC-MIC-64}$ is FALSE because even though MIC-128 offers stronger data authenticity than ENC-MIC-64, it offers no confidentiality.

9.4.2.3 Key Identifier Mode field

The Key Identifier Mode field is an unsigned integer that indicates whether the key that is used to protect the frame can be derived implicitly or explicitly; furthermore, it is used to indicate the particular representations of the Key Identifier field, as defined in 9.4.4, if derived explicitly. The Key Identifier Mode field shall be set to one of the values listed in Table 9-7. The Key Identifier field of the auxiliary security header, as defined in 9.4.4, shall be present only if this field has a value that is not equal to 0x00.

Table 9-7—Values of the Key Identifier Mode field

Key identifier mode	Key Identifier Mode field b1 b0	Description	Key Identifier field length (octets)
0x00	00	Key is determined implicitly from the originator and recipient(s) of the frame, as indicated in the frame header.	0
0x01	01	Key is determined from the Key Index field.	1
0x02	10	Key is determined explicitly from the 4-octet Key Source field and the Key Index field.	5
0x03	11	Key is determined explicitly from the 8-octet Key Source field and the Key Index field.	9

9.4.2.4 Frame Counter Suppression field

The Frame Counter Suppression field is set to zero when the frame counter is carried in the frame. When set to one, the frame counter is not carried in the frame, and the frame counter used to construct the nonce defined in 9.3.2 is an incrementing shared global frame counter such as ASN.

9.4.2.5 ASN in Nonce

The ASN in Nonce field is set to zero when the frame counter is used to generate the nonce, as described in 9.3.2.1. When set to one, the ASN is used to generate the nonce, as described in 9.3.2.2.

9.4.3 Frame Counter field

The Frame Counter field is an unsigned integer value used in nonce generation as defined in 9.3.2.1 and to provide replay protection.

The Frame Counter field may be included in each secured frame and is one of the elements required for the unsecuring operation at the recipient(s). The value of the Frame Counter field is determined by the outgoing frame security procedure, 9.2.2.

Previous versions of this standard used a single frame counter for outgoing frames for each device. The current revision of the standard allows multiple outgoing frame counters, each of which is associated with a key. If the next higher layer has been informed that the target device supports per-key frame counters, then *secFrameCounterPerKey* of the *secKeyDescriptor* may be set to TRUE. If the next higher layer of the device does not know that the target device supports per-key frame counters, then *secFrameCounterPerKey* of the *secKeyDescriptor* shall be set to FALSE.

When a frame counter, either per device or per key, reaches its maximum value, the associated keying material shall no longer be used, thus requiring this key to be updated by changing to use a new key. This provides a mechanism for ensuring that the keying material for every frame is unique and, thereby, provides for sequential freshness.

9.4.4 Key Identifier field

9.4.4.1 General

The Key Identifier field has a variable length and identifies the key that is used for cryptographic protection of outgoing frames, either explicitly or in conjunction with implicitly defined side information. The Key Identifier field shall be present only if the Key Identifier Mode field, as defined in 9.4.2.3, is set to a value different from 0x00. The Key Identifier field shall be formatted as illustrated in Figure 9-7.

Octets: 0/4/8	1
Key Source	Key Index

Figure 9-7—Format for the Key Identifier field, if present

9.4.4.2 Key Source field

The Key Source field, when present, indicates the originator of a group key. If the Key Identifier Mode field indicates a 4-octet Key Source field, then the Key Source field shall be the *macPanId* of the originator of the group key right concatenated with the *macShortAddress* of the originator of the group key. If the Key Identifier Mode field indicates an 8-octet Key Source field, then the Key Source field shall be set to the *macExtendedAddress* of the originator of the group key.

9.4.4.3 Key Index field

The Key Index field allows unique identification of different keys with the same originator.

It is the responsibility of each key originator to make sure that the actively used keys that it issues have distinct key indices and that the key indices are all different from 0x00.

9.5 Security-related MAC PIB attributes

9.5.1 Generic PIB attributes

The PIB security-related attributes are defined in Table 9-8. The model for updates to the PIB described in this standard allow the MAC to update the PIB values asynchronously to write and read requests from the next higher layer. Thus, to maintain security, implementations should use a method to update the security-related PIB attributes in a way to achieve synchronization between the next higher layer and the MAC.

Table 9-8—Security-related MAC PIB attributes

Attribute	Type	Range	Description	Default
<i>secKeyIdLookupList</i>	List of <i>secKeyIdLookupDescriptor</i> , as defined Table 9-10	—	A list of <i>secKeyIdLookupDescriptor</i> containing keys and security policy information.	(empty)
<i>secDeviceList</i>	List of <i>secDeviceDescriptor</i> , as defined in Table 9-15	—	List of device information for each remote device with which this device securely communicates.	(empty)

Table 9-8—Security-related MAC PIB attributes (continued)

Attribute	Type	Range	Description	Default
<i>secSecurityLevelList</i>	List of <i>secSecurityLevelDescriptor</i> , as defined in Table 9-16	—	Provides information about the security level required for each MAC frame type and subtype.	(empty)
<i>secFrameCounter</i>	Integer	0x00000000–0xffffffff	The outgoing frame counter for this device to be used for keys that do not have <i>secFrameCounterPerKey</i> set to TRUE.	0x00000000
<i>secAutoRequestSecurityParams</i>	Structure	As defined in Table 8-2	The security parameters used for automatic Data Request commands.	—
<i>secEnhancedBeaconSecurityParams</i>	Structure	As defined in Table 8-2	The security parameters used when transmitting Enhanced Beacons.	—
<i>secBeaconSecurityParams</i>	Structure	As defined in Table 8-2.	As defined in Table 8-2.	—

9.5.2 *secAeadAlgorithm*

Table 9-9 defines the *secAeadAlgorithm* assignments.

Table 9-9—*secAeadAlgorithm* assignments

Name	Value	Description
AES-128-CCM* ^a	0	AES-128-CCM* as described in Annex B with a 13-octet nonce as described in 9.3.2.
AES-128-CCM ^a	1	AES-128-CCM as described in Annex B with a 13-octet nonce as described in 9.3.2.
AES-256-CCM	2	AES-256-CCM as described in Annex B with a 13-octet nonce as described in 9.3.2. Test vectors for AES-256-CCM can be found in AES-256 Test Vectors [B19].
Assigned by IEEE 802.15 ANA	3 and higher assigned by IEEE 802.15 ANA	See IEEE 802.15.4 ANA database [B2].

^a AES-128-CCM and AES-128-CCM* are exactly the same except AES-128-CCM* allows using different MIC lengths with the same key.

9.5.3 *secKeyIdLookupDescriptor*

Table 9-10 defines the elements of a *secKeyIdLookupDescriptor*, which is used to find the *secKeyDescriptor* based on key identifiers.

9.5.4 *secKeyDescriptor*

Table 9-11 defines the elements of a *secKeyDescriptor*. The *secKeyDescriptor* contains one entry for each key in use by the device. More than one *secKeyIdLookupDescriptor* can point to a single *secKeyDescriptor*.

Table 9-10—Elements of *secKeyIdLookupDescriptor*

Name	Type	Range	Description
<i>secKeyIdMode</i>	Integer	As defined in Table 9-7	The mode used to for this descriptor.
<i>secKeySource</i>	4 or 8 octets	As defined in 9.4.4.2	Information to identify the key. Present only if <i>secKeyIdMode</i> is equal to 0x02 or 0x03.
<i>secKeyIndex</i>	Integer	As defined in 9.4.4.3	Information used to identify the key. Present only if <i>secKeyIdMode</i> is not equal to 0x00.
<i>secKeyDeviceAddrMode</i>	Enumeration	NONE, SHORT, EXTENDED	The addressing mode for this descriptor. Present only if <i>secKeyIdMode</i> is equal to 0x00.
<i>secKeyDevicePanId</i>	Integer	0x0000–0xffff	The PAN ID for this descriptor. Present only if <i>secKeyIdMode</i> is equal to 0x00.
<i>secKeyDeviceAddress</i>	—	As specified by the <i>secKeyDeviceAddrMode</i>	The address for this descriptor. Present only if <i>secKeyIdMode</i> is equal to 0x00.
<i>secKeyItem</i>	An <i>secKeyDescriptor</i> , as defined in Table 9-11	As defined in Table 9-11	An <i>secKeyDescriptor</i> associated with the parameters in this <i>secKeyIdLookupDescriptor</i> .

Table 9-11—Elements of *secKeyDescriptor*

Name	Type	Range	Description
<i>secKeyUsageList</i>	List of <i>secKeyUsageDescriptor</i> entries, as defined in Table 9-13	—	A list of <i>secKeyUsageDescriptor</i> entries indicating the frame types with which this key may be used.
<i>secAeadAlgorithm</i>	Integer	As defined in Table 9-9	The AEAD algorithm selected by the <i>secAeadAlgorithm</i> attribute as defined in Table 9-9.
<i>secKey</i>	Set of octets	—	The value of the key sized to the requirements of <i>secAeadAlgorithm</i> .
<i>secKeyFrameCounter</i>	Integer	0x00000000–0xffffffff	The outgoing frame counter for this key. This not used if <i>secFrameCounterPerKey</i> is FALSE.

Table 9-11—Elements of *secKeyDescriptor* (continued)

Name	Type	Range	Description
<i>secFrameCounterPerKey</i>	Boolean	TRUE, FALSE	If this value is TRUE, this key will use per key frame counters stored in <i>secKeyDescriptor</i> and <i>secKeyDeviceFrameCounterDescriptor</i> entries. If this value is FALSE, then per device frame counters are used for this key.
<i>secKeyDeviceFrameCounterList</i>	List of <i>secKeyDeviceFrameCounterDescriptor</i> entries, as defined in Table 9-12	—	A list of <i>secKeyDeviceFrameCounterDescriptor</i> entries containing the per key frame counters used for this <i>secKeyDescriptor</i> .

9.5.5 *secKeyDeviceFrameCounterDescriptor*

Table 9-12 defines the elements of a *secKeyDeviceFrameCounterDescriptor*, which contains the incoming frame counter for a device specified by the associated extended address.

Table 9-12—Elements of *secKeyDeviceFrameCounterDescriptor*

Name	Type	Range	Description
<i>secDeviceExtAddress</i>	IEEE address	An extended IEEE address	The extended address of the device associated with the <i>secKeyDeviceFrameCounterDescriptor</i> .
<i>secDeviceFrameCounter</i>	Integer	0x00000000–0xffffffff	The incoming frame counter for the device indicated by <i>secDeviceExtAddress</i> .

9.5.6 *secKeyUsageDescriptor*

Table 9-13, defines the elements of a *secKeyUsageDescriptor*. Each entry of a *secKeyUsageDescriptor* corresponds to a key and is used to define the frame types, MAC commands, and IEs that are allowed to be used with that key.

Table 9-13—Elements of *secKeyUsageDescriptor*

Name	Type	Range	Description
<i>secKeyUsageFrameType</i>	Integer	As defined in 7.2.2.2	As defined in 7.2.2.2.
<i>secKeyUsageCommandId</i>	Integer	As defined in Table 7-11	As defined in Table 7-11.
<i>secKeyIeUsageDescriptorList</i>	List of <i>secKeyIeUsageDescriptor</i> entries, as defined in Table 9-14	—	List of <i>secKeyIeUsageDescriptor</i> entries. If this is empty, then there are no restrictions on the IE usage associated with the key.

9.5.7 secKeyIeUsageDescriptor

Table 9-14 defines the elements of a *secKeyIeUsageDescriptor*. The *secKeyIeUsageDescriptor* is a list of IEs that are allowed to be used with a key.

Table 9-14—Elements of secKeyIeUsageDescriptor

Name	Type	Range	Description
<i>secKeyIeType</i>	Enumeration	HEADER, PAYLOAD, NESTED_SHORT, NESTED_LONG	The type of IE, header, payload, nested long format or nested short format, as defined in 7.4.
<i>secKeyIeId</i>	Integer	As defined in Table 7-7, Table 7-8, Table 7-9, or Table 7-10	The IE ID for the IE type indicated by <i>secKeyIeType</i> .

9.5.8 secDeviceDescriptor

Table 9-15 defines the elements of a *secDeviceDescriptor*. Each entry in *secDeviceDescriptor* contains information about a device in the PAN with which this device has communicated.

Table 9-15—Elements of secDeviceDescriptor

Name	Type	Range	Description
<i>secPanId</i>	Device PAN ID	0x0000–0xffff	The PAN ID of the device in this <i>secDeviceDescriptor</i> .
<i>secShortAddress</i>	Device short address	0x0000–0xffff	The short address of the device in this <i>secDeviceDescriptor</i> . A value of 0xfffe indicates that this device is using only its extended address. A value of 0xffff indicates that this value is unknown.
<i>secExtAddress</i>	IEEE address	Any valid extended IEEE address	The extended IEEE address of the device.
<i>secExempt</i>	Boolean	TRUE, FALSE	Indication of whether the device may override the minimum security level settings defined in Table 9-16.
<i>secDeviceMinFrameCounter</i>	Integer	0x00000000–0xffffffff	The smallest frame counter allowed to be sent by the other device for this key. If the incoming frame counter is smaller than this, then the frame is replayed.

9.5.9 secSecurityLevelDescriptor

The security policies for frames and IEs are contained in the *secSecurityLevelDescriptor*. The elements of *secSecurityLevelDescriptor* are defined in Table 9-16.

Table 9-16—Elements of *secSecurityLevelDescriptor*

Name	Type	Range	Description
<i>secFrameType</i>	Integer	As defined in 7.2.2.2	As defined in 7.2.2.2.
<i>secCommandId</i>	Integer	As defined in Table 7-11	As defined in Table 7-11.
<i>secDeviceOverrideSecurityLevels</i>	Boolean	TRUE, FALSE	Indication of whether originating devices for which the <i>secExempt</i> is set may override the security level indicated by the <i>secAllowedSecurityLevels</i> . If TRUE, this indicates that for originating devices the incoming security level zero is acceptable.
<i>secAllowedSecurityLevels</i>	Set of tuples of <i>secAlgorithm</i> , SecurityLevel	—	A set of allowed algorithm identifier and security levels tuples, as defined in Table 9-9 and Table 9-6, respectively, for incoming MAC frames with the indicated frame type, and, if present, Command ID field.
<i>secIeSecurityLevelDescriptorList</i>	List of <i>secIeSecurityLevelDescriptor</i> entries, as defined in Table 9-17	—	The allowed security levels for IEs. If this is empty, then there are no restrictions on security levels for IEs.

9.5.10 *secIeSecurityLevelDescriptor*

The *secIeSecurityLevelDescriptor* contains the security policies for IEs. The elements of the *secIeSecurityLevelDescriptor* are defined in Table 9-17.

Table 9-17—Elements of *secIeSecurityLevelDescriptor*

Name	Type	Range	Description
<i>secIeType</i>	Enumeration	HEADER, PAYLOAD, NESTED_SHORT, NESTED_LONG	The type of IE, header, payload, nested long format or nested short format, as defined in 7.4.
<i>secIeId</i>	Integer	As defined in Table 7-7, Table 7-8, Table 7-9, or Table 7-10	The IE ID for the IE type indicated by <i>secIeType</i> .
<i>secIeDeviceOverrideSecurityLevels</i>	As defined in Table 9-16	As defined in Table 9-16	As defined in Table 9-16.
<i>secIeAllowedSecurityLevels</i>	As defined in Table 9-16	As defined in Table 9-16	As defined in Table 9-16.

10. Optional features

10.1 General

All features in this clause are optional and each subclause describes one optional feature. Some features do require other optional features to be implemented, for example multi-node ranging specified in 10.32 requires basic ranging specified in 10.29.

10.2 Superframe structure

10.2.1 Overview of superframe structure

The format of the superframe is defined by the coordinator. The superframe is bounded by beacons (either Beacon frames or Enhanced Beacon frames) sent by the coordinator. Optionally, the superframe can have an active and an inactive portion. During the inactive portion, the coordinator is able to enter a low-power mode. The beacon frame transmission starts at the beginning of the first slot of each superframe. If a coordinator does not wish to use a superframe structure, it will turn off the beacon transmissions. The beacons are used to synchronize the attached devices, to identify the PAN, and to describe the structure of the superframes.

The period between two beacons where devices can randomly access the medium is defined as CAP. Any device wishing to communicate during the CAP between two beacons competes with other devices using a slotted CSMA-CA or ALOHA mechanism, as appropriate. For low-latency applications or applications requiring specific data bandwidth, the PAN coordinator dedicates portions of the active superframe to that application. These portions are called GTSs. The GTSs form the contention-free period (CFP), which always appears at the end of the active superframe starting at a slot boundary immediately following the CAP. The PAN coordinator allocates up to seven of these GTSs, and a GTS is allowed to occupy more than one slot period. However, a sufficient portion of the CAP remains for contention-based access of other networked devices or new devices wishing to join the network. All contention-based transactions are completed before the CFP begins. If there is insufficient time to complete the transaction before the time of the next GTS or the end of the CFP, the device transmitting in the GTS shall defer its transaction.

10.2.2 Channel access

10.2.2.1 General

A coordinator of a PAN may use a superframe structure. A superframe is bounded by the transmission of a Beacon frame and may have an active portion and an inactive portion. The coordinator may enter a low-power (sleep) mode during the inactive portion.

For LE-applications an optional superframe structure may be used, as described in 10.5.2.

The structure of this superframe is described by the values of *macBeaconOrder* and *macSuperframeOrder*. The MAC PIB attribute *macBeaconOrder* describes the interval at which the coordinator shall transmit its Beacon frames. The value of *macBeaconOrder* and the beacon interval (*BI*) are related as follows:

$$BI = aBaseSuperframeDuration \times 2^{macBeaconOrder}$$

for

$$0 \leq macBeaconOrder \leq 14$$

If $macBeaconOrder = 15$, the coordinator shall not transmit Beacon frames except when requested to do so, such as on receipt of a Beacon Request command. The value of $macSuperframeOrder$ shall be ignored if $macBeaconOrder = 15$.

The MAC PIB attribute $macSuperframeOrder$ describes the length of the active portion of the superframe, which includes the Beacon frame. The value of $macSuperframeOrder$, and the superframe duration (SD) are related as follows:

$$SD = aBaseSuperframeDuration \times 2^{macSuperframeOrder}$$

for

$$0 \leq macSuperframeOrder \leq macBeaconOrder \leq 14$$

If $macSuperframeOrder = 15$, the superframe shall not remain active after the beacon. If $macBeaconOrder = 15$, the superframe shall not exist (the value of $macSuperframeOrder$ shall be ignored), and $macRxOnWhenIdle$ shall define whether the receiver is enabled during periods of transceiver inactivity.

The active portion of each superframe shall be divided into $aNumSuperframeSlots$ equally spaced slots of duration $2^{macSuperframeOrder} \times aBaseSlotDuration$ and is composed of a beacon, a CAP, and a CFP. The beacon shall be transmitted, without the use of CSMA, at the start of slot 0, and the CAP shall commence immediately following the beacon. The start of slot 0 is defined as the point at which the first symbol of the beacon PPDU is transmitted. The CFP, if present, follows immediately after the CAP and extends to the end of the active portion of the superframe. Any allocated GTSs shall be located within the CFP.

PANs that wish to use the superframe structure (which used to be referred to as beacon-enabled PANs) shall set $macBeaconOrder$ to a value between 0 and 14, both inclusive, and $macSuperframeOrder$ to a value between 0 and the value of $macBeaconOrder$, both inclusive.

PANs that do not wish to use the superframe structure (which used to be referred to as nonbeacon-enabled PANs) shall set both $macBeaconOrder$ and $macSuperframeOrder$ to 15. In this case, a coordinator shall not transmit beacons, except upon receipt of a Beacon Request command; all transmissions, with the exception of Ack frames and any Data frame that quickly follows the acknowledgment of a Data Request command, as described in 10.22.3, shall use an unslotted CSMA-CA mechanism to access the channel. In addition, GTSs shall not be permitted.

An example of a superframe structure is shown in Figure 10-1. In this case, the beacon interval, BI , is twice as long as the active SD , and the CFP contains two GTSs.

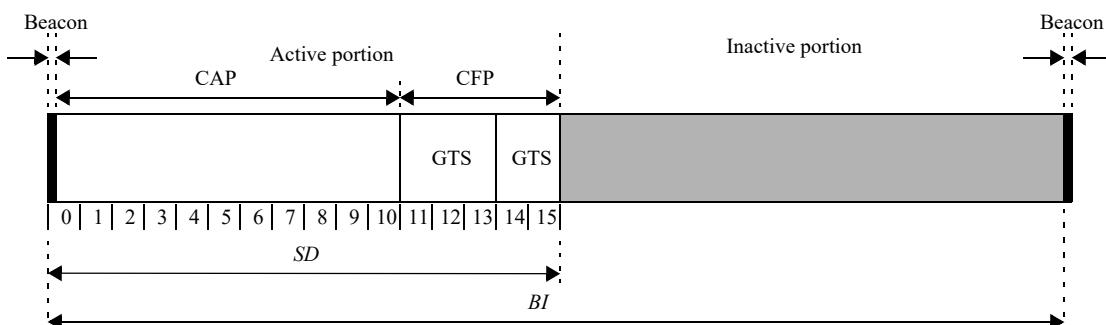


Figure 10-1—An example of the superframe structure

When operating as a TMCTP, the superframe includes the beacon only period (BOP), as described in 10.2.2.4, and the structure of the superframe is described in 10.8.2.

10.2.2.2 Contention access period (CAP)

The CAP shall start immediately following the beacon and complete before the beginning of the CFP on a superframe slot boundary. If the CFP is zero length, the CAP shall complete at the end of the active portion of the superframe. The CAP shall be at least *aMinCapLength*, unless additional space is needed to temporarily accommodate the increase in the Beacon frame length needed to perform GTS maintenance, as described in 7.3.1.5, and shall shrink or grow dynamically to accommodate the size of the CFP.

All frames, except Ack frames and any Data frame that quickly follows the acknowledgment of a Data Request command, as described in 10.2.2.3, transmitted in the CAP shall use a slotted CSMA-CA mechanism to access the channel. A device transmitting within the CAP shall ensure that its transaction is complete (i.e., including the reception of a minimum length acknowledgment) one interframe spacing (IFS) period, as described in 6.3.1, before the end of the CAP. If this is not possible, the device shall defer its transmission until the CAP of the following superframe.

10.2.2.3 Contention-free period (CFP)

The CFP shall start on a slot boundary immediately following the CAP, and it shall complete before the end of the active portion of the superframe. If any GTSs have been allocated by the PAN coordinator, they shall be located within the CFP and occupy contiguous slots. The duration of the CFP, therefore, changes depending on the total duration of all of the combined GTSs.

No transmissions within the CFP shall use a CSMA-CA mechanism to access the channel. A device transmitting in the CFP shall ensure that its transmissions are complete one IFS period, as described in 6.3.1, before the end of its GTS.

10.2.2.4 Beacon only period (BOP)

When present, the BOP shall commence on the slot boundary immediately following the CFP, if the CFP is present. When there is no CFP, the BOP shall commence on the slot boundary immediately following the CAP. The BOP shall complete before the end of the active portion of the superframe. The BOP duration depends on the number of DBSs, one of which is allocated to each TMCTP-child PAN coordinator. All DBSs shall be located within the BOP and occupy contiguous slots. The BOP, therefore, grows or shrinks depending on the total length of all of the combined DBSs. Multiple base slots in the BOP can be allocated to a DBS according to the length of the beacon to be sent by the TMCTP-child coordinator that will occupy the DBS.

CSMA-CA is not used for beacon transmissions in the BOP. A TMCTP-child PAN coordinator transmitting in the BOP shall ensure that its beacon transmission is complete prior to one IFS period before the end of its DBS. The IFS period is described in 6.3.1.

10.2.2.5 Incoming and outgoing superframe timing

On a PAN using superframe structure, a coordinator that is not the PAN coordinator shall maintain the timing of both the superframe in which its coordinator transmits a beacon (the incoming superframe) and the superframe in which it transmits its own beacon (the outgoing superframe). The relative timing of these superframes is defined by the StartTime parameter of the MLME-START-SUPERFRAME.request primitive, as described in 10.2.9.2 and 10.2.4. The relationship between incoming and outgoing superframes is illustrated in Figure 10-2. If a device receives a Coordinator Realignment command from its coordinator indicating that the coordinator will begin using a new superframe configuration, the device shall ensure that its own beacons do not overlap with the beacons transmitted by the coordinator. If the new superframe

configuration causes the incoming and outgoing superframes to overlap, the device shall stop transmitting its beacons immediately and notify the next higher layer via the MLME-SYNC-LOSS.indication primitive, as described in 10.2.10.3, with the LossReason parameter set to SUPERFRAME_OVERLAP.

The beacon order and superframe order shall be equal for all superframes on a PAN. All devices shall interact with the PAN only during the active portion of a superframe.

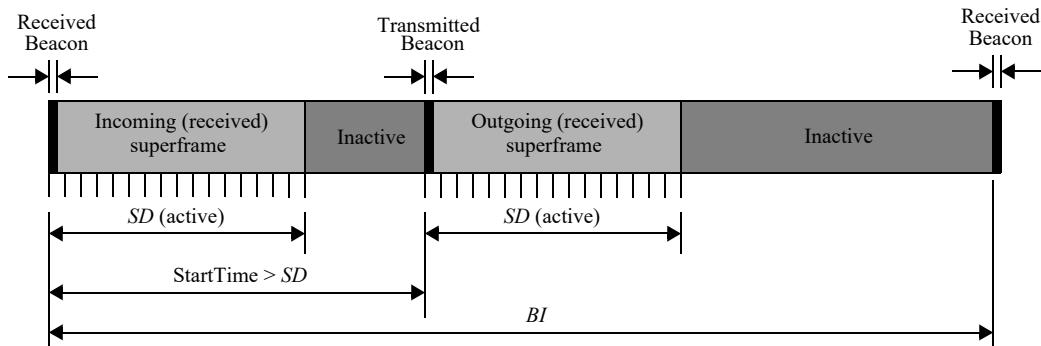


Figure 10-2—The relationship between incoming and outgoing beacons

10.2.2.6 Updating superframe configuration and channel PIB attributes

To update the superframe configuration and channel attributes, the MLME shall assign values from the MLME-START-SUPERFRAME.request primitive parameters to the appropriate PIB attributes. The MLME shall set *macBeaconOrder* to the value of the BeaconOrder parameter. If *macBeaconOrder* is equal to 15, the MLME will also set *macSuperframeOrder* to 15. In this case, this primitive configures a PAN not using superframe structure. If *macBeaconOrder* is less than 15, the MAC sublayer will set *macSuperframeOrder* to the value of the SuperframeOrder parameter. The MAC sublayer shall also update *macPanId* with the value of the PanId parameter and *phyCurrentChannelInfo* with the value of the ChannelInfo parameter.

10.2.3 Starting and realigning a PAN

10.2.3.1 Starting a PAN in superframe structure

On receipt of MLME-START-SUPERFRAME.request primitive, the MAC sublayer shall update the superframe configuration and channel parameters as specified in 10.2.2.6. After completing this, the MAC sublayer shall issue the MLME-START-SUPERFRAME.confirm primitive, as described in 10.2.9.3, with a Status of SUCCESS and begin operating as the PAN coordinator.

A example of a message sequence chart for starting a PAN when using superframe structure is illustrated in Figure 10-3.

10.2.3.2 Realigning a PAN

If a coordinator receives the MLME-START-SUPERFRAME.request primitive, as defined in 10.2.9.2, with the CoordRealignment parameter set to TRUE, the coordinator shall attempt to transmit a Coordinator Realignment command containing the new parameters for PanId and ChannelInfo.

When the coordinator is already transmitting beacons and the CoordRealignment parameter is set to TRUE, the next scheduled beacon shall be transmitted on the current channel using the current configuration, with the Frame Pending field set to one. Immediately following the transmission of the beacon, the Coordinator Realignment command shall also be transmitted on the current channel using CSMA-CA.

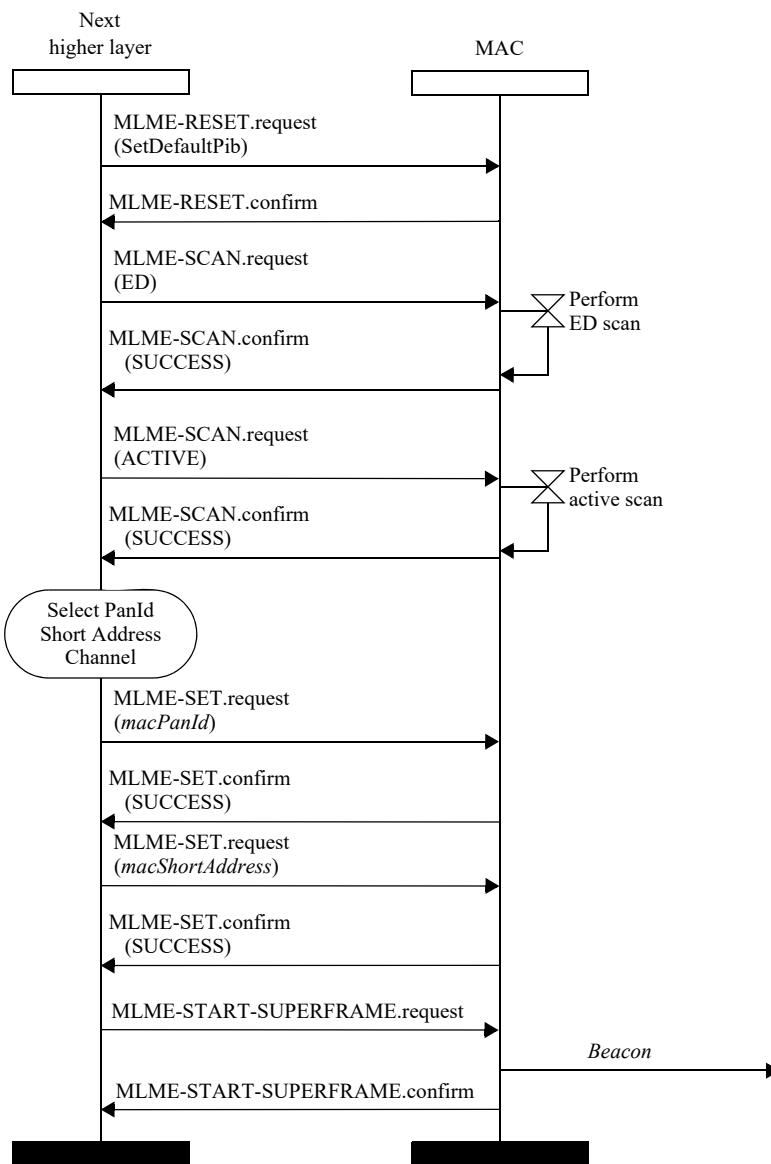


Figure 10-3—PAN start message sequence chart—PAN coordinator using superframe structure

When the coordinator is not already transmitting beacons and the CoordRealignment parameter is set to TRUE, the Coordinator Realignment command shall be transmitted immediately on the current channel using CSMA-CA.

If the transmission of the Coordinator Realignment command fails due to a channel access failure, the MLME shall notify the next higher layer by issuing the MLME-START-SUPERFRAME.confirm primitive with a Status of CHANNEL_ACCESS_FAILURE. The next higher layer may then choose to issue the MLME-START-SUPERFRAME.request primitive again.

Upon successful transmission of the Coordinator Realignment command, the new configuration and channel parameters shall be put into operation at the subsequent scheduled beacon, or immediately if the coordinator

is not already transmitting beacons, and the MAC sublayer shall issue the MLME-START-SUPERFRAME.confirm primitive with a Status of SUCCESS.

10.2.3.3 Device discovery

The PAN coordinator or a coordinator indicates its presence on a PAN to other devices by transmitting Beacon frames. This allows the other devices to perform device discovery.

A coordinator that is not the PAN coordinator shall begin transmitting Beacon frames only when it has successfully associated with a PAN. The transmission of Beacon frames by the device is initiated through the use of the MLME-START-SUPERFRAME.request primitive with the PanCoordinator parameter set to FALSE. On receipt of this primitive, the MLME shall begin transmitting beacons based on the StartTime parameter, as described in 10.2.4, using the identifier of the PAN with which the device has associated, *macPanId*, and its extended address, *macExtendedAddress*, if *macShortAddress* is equal to 0xffffe, or its short address, *macShortAddress*, otherwise. A Beacon frame shall be transmitted at a rate of one Beacon frame every $aBaseSuperframeDuration \times 2^n$, where n is the value of *macBeaconOrder*.

10.2.4 Beacon generation

A device shall use the MLME-START-SUPERFRAME.request primitive to begin transmitting beacons only if the BeaconOrder parameter is less than 15. The device may begin beacon transmission either as the PAN coordinator of a new PAN or as a device on a previously established PAN, depending upon the setting of the PanCoordinator parameter, as defined in 10.2.9.2. The device shall begin beacon transmission on a previously established PAN only once it has successfully associated with that PAN.

If the device is the PAN coordinator (i.e., the PanCoordinator parameter is set to TRUE), the MAC sublayer shall ignore the StartTime parameter and begin beacon transmissions immediately. Setting the StartTime parameter to zero shall also cause the MAC sublayer to begin beacon transmissions immediately. If the device is not the PAN coordinator and the StartTime parameter is nonzero, the time to begin beacon transmissions shall be calculated using the following method. The StartTime parameter, which is rounded to a backoff period boundary, shall be added to the time, obtained from the local clock, when the MAC sublayer receives the beacon of the coordinator through which it is associated. The MAC sublayer shall then begin beacon transmissions when the current time, obtained from the local clock, equals the calculated time. In order for the beacon transmission time to be calculated by the MAC sublayer, the MAC sublayer shall first track the beacon of the coordinator through which it is associated. If the MLME-START-SUPERFRAME.request primitive is issued with a nonzero StartTime parameter and the MAC sublayer is not currently tracking the beacon of its coordinator, the MLME shall not begin beacon transmissions but shall instead issue the MLME-START-SUPERFRAME.confirm primitive with a Status of TRACKING_OFF.

If a device misses between one and (*aMaxLostBeacons* – 1) consecutive Beacon frames from its coordinator, the device shall continue to transmit its own beacons based on both *macBeaconOrder*, as defined in 10.2.2.6, and its local clock. If the device then receives a Beacon frame from its coordinator and, therefore, does not lose synchronization, the device shall resume transmitting its own beacons based on the StartTime parameter and the incoming beacon. If a device misses *aMaxLostBeacons* consecutive Beacon frames from its coordinator, the MLME of the device shall issue the MLME-SYNC-LOSS.indication primitive to the next higher layer and immediately stop transmitting its own beacons. The next higher layer may, at any time following the reception of the MLME-SYNC-LOSS.indication primitive, resume beacon transmissions by issuing a new MLME-START-SUPERFRAME.request primitive.

On receipt of the MLME-START-SUPERFRAME.request primitive, the MAC sublayer shall set the PAN ID in *macPanId* and use this value in the Source PAN ID field of the Beacon frame. The address used in the Source Address field of the Beacon frame shall contain the value of *macExtendedAddress* if *macShortAddress* is equal to 0xffffe or *macShortAddress* otherwise.

The time of transmission of the most recent beacon shall be recorded in *macBeaconTxTime* and shall be computed so that its value is taken at the same symbol boundary in each Beacon frame, the location of which is implementation specific. The symbol boundary, which is specified by the *macSyncSymbolOffset* attribute, is the same as that used in the timestamp of the incoming Beacon frame, as described in 10.2.6.

All Beacon frames, as defined in 7.3.1, shall be transmitted at the beginning of each superframe at an interval equal to $aBase-SuperframeDuration \times 2^n$, where n is the value of *macBeaconOrder*.

For devices operating in a PAN using superframe structure, a coordinator may precede beacon transmission with listen before talk (LBT) without random backoff.

Beacon transmissions shall be given priority over all other transmit and receive operations.

10.2.5 Realignment in a PAN

If a device has received the Coordinator Realignment command, as defined in 7.5.4, from the coordinator through which it is associated and the MLME was not carrying out an orphan scan, the MLME shall issue the MLME-SYNC-LOSS.indication primitive with the LossReason parameter set to REALIGNMENT and the PanId, ChannelInfo, and the security-related parameters set to the respective fields in the Coordinator Realignment command. The next higher layer of a coordinator may then issue an MLME-START-SUPERFRAME.request primitive with the CoordRealignment parameter set to TRUE. The next higher layer of a device that is not a coordinator may instead change the superframe configuration or channel parameters through use of the MLME-SET.request primitive, as described in 8.2.5.4.

10.2.6 Synchronization with beacons

All devices operating on a PAN using superframe structure (i.e., $macBeaconOrder < 15$) shall be able to acquire beacon synchronization in order to detect any pending messages or to track the beacon. Devices shall be permitted to acquire beacon synchronization only with beacons containing the PAN ID specified in *macPanId*. If *macPanId* specifies the broadcast PAN ID, a device shall not attempt to acquire beacon synchronization.

A device is instructed to attempt to acquire the beacon through the MLME-SYNC.request primitive. If tracking is specified in the MLME-SYNC.request primitive, the device shall attempt to acquire the beacon and keep track of it by regular and timely activation of its receiver. If tracking is not specified, the device shall either attempt to acquire the beacon only once or terminate the tracking after the next beacon if tracking was enabled through a previous request.

To acquire beacon synchronization, a device shall enable its receiver and search for at most $[aBaseSuperframeDuration \times (2^n + 1)]$, where n is the value of *macBeaconOrder*. If a Beacon frame containing the current PAN ID of the device is not received, the MLME shall repeat this search. Once the number of missed beacons reaches *aMaxLostBeacons*, the MLME shall notify the next higher layer by issuing the MLME-SYNC-LOSS.indication primitive with a loss reason of BEACON_LOST.

The MLME shall timestamp each received Beacon frame at the same symbol boundary within each frame, the location of which is described by the *macSyncSymbolOffset* attribute. The symbol boundary shall be the same as that used in the timestamp of the outgoing Beacon frame, stored in *macBeaconTxTime*. Timestamps are specified in 6.5.3.

If a protected Beacon frame is received (i.e., the Security Enabled field is set to one), the device shall attempt to unsecure the Beacon frame using the unsecuring process described in 9.2.4.

If the Status from the unsecuring process is not SUCCESS, the MLME shall issue an MLME-COMM-STATUS.indication primitive, as described in 8.2.4.4, with the Status parameter set to the Status from the unsecuring process, indicating the error.

The security-related elements of the PAN descriptor corresponding to the beacon, as defined in Table 8-3, shall be set to the corresponding parameters returned by the unsecuring process. The SecurityStatus element of the PAN descriptor shall be set to SUCCESS if the Status from the unsecuring process is SUCCESS and set to one of the other Status codes indicating an error in the security processing otherwise.

If the Status from the unsecuring process is not SUCCESS, the MAC shall then discard the Beacon frame.

If the Source Address and the Source PAN ID fields of the MHR of the Beacon frame do not match the coordinator source address (*macCoordShortAddress* or *macCoordExtendedAddress*, depending on the addressing mode) and the PAN ID of the device (*macPanId*), then the Beacon frame is a tracking Beacon frame.

If the Beacon frame that was received is a tracking Beacon frame or if *macNotifyAllBeacons* is TRUE, then the MLME shall indicate the beacon parameters to the next higher layer by issuing the MLME-BEACON-NOTIFY.indication primitive.

If *macAutoRequest* is set to TRUE, the MLME shall then compare its address with those addresses in the Address List field of the Beacon frame. If the Address List field contains the short address or extended address of the device and the source PAN ID matches *macPanId*, the MLME shall follow the procedure for extracting pending data from the coordinator, as described in 10.22.

If beacon tracking is activated, the MLME shall enable its receiver at a time prior to the next expected Beacon frame transmission, i.e., just before the known start of the next superframe. If the number of consecutive tracking Beacons frames missed by the MLME reaches *aMaxLostBeacons*, the MLME shall respond with the MLME-SYNC-LOSS.indication primitive with a loss reason of BEACON_LOST.

In Figure 10-4, the next higher layer issues a synchronization request with TrackBeacon set to FALSE. The MLME then searches for a beacon and, if found, determines whether the coordinator has any data pending for the device. If so, the data are requested as described in 10.22.

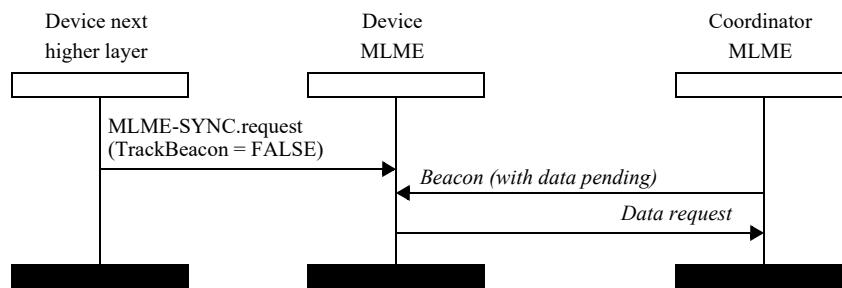


Figure 10-4—Synchronizing to a coordinator in a PAN using superframe structure without tracking beacons

In Figure 10-5, the next higher layer issues a synchronization request with TrackBeacon set to TRUE. The MLME then searches for a beacon and, if found, attempts to keep track of it using a timer that expires just before the expected time of the next beacon.

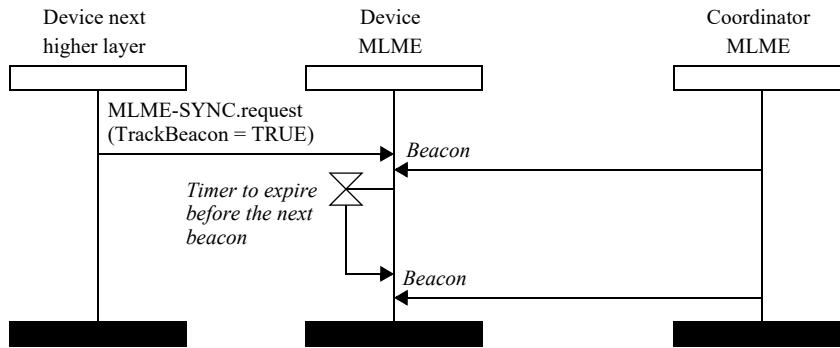


Figure 10-5—Synchronizing to a coordinator in a PAN using superframe structure while tracking beacons

10.2.7 Transmission when using superframe structure

If the frame is to be transmitted on a PAN using superframe structure, the transmitting device shall attempt to find the beacon before transmitting. If the beacon is not being tracked, as described in 10.2.6, and hence the device does not know where the beacon will appear, it shall enable its receiver and search for at most [$aBaseSuperframeDuration \times (2^n + 1)$], where n is the value of *macBeaconOrder*, in order to find the beacon. If the beacon is not found after this time, the device shall transmit the frame following the successful application of the unslotted version of the CSMA-CA algorithm, as described in 6.3.2. Once the beacon has been found, either after a search or due to its being tracked, the frame shall be transmitted in the appropriate portion of the superframe. Transmissions in the CAP shall follow a successful application of the slotted version of the CSMA-CA algorithm, as described in 6.3.2.

When the LECIM DSSS PHY is in use in a PAN using superframe structure, transmissions after the beacon shall commence *phyLecimDsssPpduTxAt* following the reception of the last symbol of the Beacon frame.

10.2.8 Header IEs for superframe structure

10.2.8.1 Simplified Superframe Specification IE

The Simplified Superframe Specification IE Content field shall be formatted as illustrated in Figure 10-6.

Octets: 2	2	2
Timestamp	Superframe Specification	CFP Specification

Figure 10-6—Simplified Superframe Specification IE Content field format

The Timestamp field shall be updated between transmissions; the initial value, resolution (LSB value), and accuracy are implementation dependent.

The Superframe Specification field is as defined in 7.3.1.4.

The CFP Specification field shall be encoded as illustrated in Figure 10-7.

Bits: 0–3	4–7	8–11	12	13–15
Number of GTSs	First CFP Slot in Superframe	Last CFP Slot in Superframe	GTS Permit	Reserved

Figure 10-7—CFP Specification field format

The Number of GTSs field shall be set to the number of GTSs allocated by the coordinator.

The First CFP Slot in Superframe field shall be set to the slot number in which the CFP begins.

The Last CFP Slot in Superframe field shall be set to the slot number in which the CFP ends.

The GTS Permit field shall be set to one if *macGtsPermit* is equal to TRUE, indicating that the coordinator is accepting GTS requests. Otherwise, the field shall be set to zero.

10.2.9 Primitives for updating the superframe configuration

10.2.9.1 General

These primitives are used by a device to initiate a PAN, to begin using a new superframe configuration, or to stop transmitting beacons. In addition, a device uses these primitives to begin using a new superframe configuration.

10.2.9.2 MLME-START-SUPERFRAME.request

The MLME-START-SUPERFRAME.request primitive is used by the PAN coordinator to initiate a new PAN or to begin using a new superframe configuration. This primitive is also used by a device already associated with an existing PAN to begin using a new superframe configuration.

The semantics of this primitive are as follows:

```
MLME-START-SUPERFRAME.request(
    PanId,
    ChannelInfo,
    StartTime,
    BeaconOrder,
    SuperframeOrder,
    PanCoordinator,
    BatteryLifeExtension,
    CoordRealignment,
    CoordRealignSecurityParams,
    BeaconSecurityParams,
    HeaderleList,
    PayloadleList,
    HeaderleIdList,
    NestedleSubIdList,
)
```

The primitive parameters are defined in Table 10-1.

Table 10-1—MLME-START-SUPERFRAME.request parameters

Name	Type	Valid range	Description
PanId	Integer	0x0000–0xffff	The PAN ID to be used by the device.
ChannelInfo	Channel information structure as defined in 11.1.3.1	Any valid channel	The channel to use.
StartTime	Integer	0x000000–0xffffffff	The time at which to begin transmitting beacons. If this parameter is equal to 0x000000, beacon transmissions will begin immediately. Otherwise, the specified time is relative to the received Beacon frame of the coordinator with which the device synchronizes. This parameter is ignored if either the BeaconOrder parameter has a value of 15 or the PanCoordinator parameter is TRUE. This parameter is ignored in a DSME-enabled PAN. Timestamps are specified in 6.5.3.
BeaconOrder	Integer	0–15	Indicates the frequency with which the beacon is transmitted.
SuperframeOrder	Integer	0–BO or 15	The length of the active portion of the superframe, including the beacon frame.
PanCoordinator	Boolean	TRUE, FALSE	If this value is TRUE, the device will become the PAN coordinator of a new PAN. If this value is FALSE, the device will begin using a new superframe configuration on the PAN with which it is associated.
BatteryLifeExtension	Boolean	TRUE, FALSE	If this value is TRUE, the receiver of the beaconing device is disabled <i>macBattLifeExtPeriods</i> full backoff periods after the IFS period following the beacon frame. If this value is FALSE, the receiver of the beaconing device remains enabled for the entire CAP. This parameter is ignored if the BeaconOrder parameter has a value of 15.
CoordRealignment	Boolean	TRUE, FALSE	TRUE if a Coordinator Realignment command is to be transmitted prior to changing the superframe configuration or FALSE otherwise.
CoordRealignSecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.
BeaconSecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.
HeaderIeList	Set of IEs as described in 7.4.2	—	The header IEs, excluding Termination IEs, that are to be included in the Beacon frame, in addition to any header IEs added by the MAC.
PayloadIeList	Set of IEs as described in 7.4.3	—	The payload IEs, excluding Termination IEs, that are to be included in the Beacon frame, in addition to any payload IEs added by the MAC.

Table 10-1—MLME-START-SUPERFRAME.request parameters (continued)

Name	Type	Valid range	Description
HeaderIeIdList	Set of header IE IDs, as described in Table 7-7	—	The IDs of header IEs, excluding Termination IEs, to be added to the Beacon frame. The MAC will provide the content for the IE.
NestedIeSubIdList	Set of Nested IE sub-IDs, as described in Table 7-9 and Table 7-10	—	The sub-IDs of nested IEs, excluding Termination IEs, to be added to the Beacon frame. The MAC will provide the content for the IE.

When the CoordRealignment parameter is set to TRUE, the coordinator attempts to transmit a Coordinator Realignment command as described in 7.5.4. If the transmission of the Coordinator Realignment command fails due to a channel access failure, the MLME will not make any changes to the superframe configuration (i.e., no PIB attributes will be changed). If the Coordinator Realignment command is successfully transmitted, the MLME updates the PIB attributes BeaconOrder, SuperframeOrder, PanId, and ChannelInfo parameters.

When the CoordRealignment parameter is set to FALSE, the MLME updates the appropriate PIB attributes with the values of the BeaconOrder, SuperframeOrder, PanId, and ChannelInfo parameters, as described in 10.2.2.6.

The address used by the coordinator in its beacon frames is determined by the current value of *macShortAddress*, which is set by the next higher layer before issuing this primitive. If the BeaconOrder parameter is less than 15, the MLME sets *macBattLifeExt* to the value of the BatteryLifeExtension parameter. If the BeaconOrder parameter equals 15, the value of the BatteryLifeExtension parameter is ignored.

If the CoordRealignment parameter is set to TRUE, the CoordRealignSecurityParams parameter will be used to process the MAC command. If the BeaconOrder parameter indicates a beacon-enabled network, the BeaconSecurityParam parameter will be used to process the beacon frame.

If the BeaconOrder parameter is less than 15, the MLME examines the StartTime parameter to determine the time to begin transmitting beacons. If the PAN coordinator parameter is set to TRUE, the MLME ignores the StartTime parameter and begins beacon transmissions immediately. Setting the StartTime parameter to 0x000000 also causes the MLME to begin beacon transmissions immediately. If the PanCoordinator parameter is set to FALSE and the StartTime parameter is nonzero, the MLME calculates the beacon transmission time by adding StartTime to the time, obtained from the local clock, when the MLME receives the beacon of the coordinator through which it is associated. If the time calculated causes the outgoing superframe to overlap the incoming superframe, the MLME shall not begin beacon transmissions. Otherwise, the MLME then begins beacon transmissions when the current time, obtained from the local clock, equals the calculated time.

If *macUseEnhancedBeacon* is TRUE, the MLME shall use enhanced beacons rather than standard beacons containing the IEs provided. The enhanced beacon shall be secured according to the value of the BeaconSecurityParams parameter.

10.2.9.3 MLME-START-SUPERFRAME.confirm

The MLME-START-SUPERFRAME.confirm primitive reports the results of the attempt to start using a new superframe configuration.

The semantics of this primitive are as follows:

```
MLME-START-SUPERFRAME.confirm(
    Status
)
```

The primitive parameters are defined in Table 10-2.

Table 10-2—MLME-START-SUPERFRAME.confirm parameters

Name	Type	Valid range	Description
Status	Enumeration	SUCCESS, NO_SHORT_ADDRESS, SUPERFRAME_OVERLAP, TRACKING_OFF, also see 8.2.2	The result of the attempt to start using an updated superframe configuration.

The MLME-START-SUPERFRAME.confirm primitive is generated by the MLME and issued to its next higher layer in response to an MLME-START-SUPERFRAME.request primitive. The MLME-START-SUPERFRAME.confirm primitive returns a Status of either SUCCESS, indicating that the MAC sublayer has started using the new superframe configuration, or the appropriate error code as follows:

- NO_SHORT_ADDRESS: The *macShortAddress* is set to 0xffff.
- SUPERFRAME_OVERLAP: The outgoing superframe overlaps the incoming superframe.
- TRACKING_OFF: The StartTime parameter is nonzero, and the MLME is not currently tracking the beacon of the coordinator through which it is associated.

10.2.10 Primitives for synchronizing with a coordinator

10.2.10.1 General

These primitives are used to synchronize with a coordinator and to communicate loss of synchronization to the next higher layer.

10.2.10.2 MLME-SYNC.request

The MLME-SYNC.request primitive requests to synchronize with the coordinator by acquiring and, if specified, tracking its beacons.

The semantics of this primitive are as follows:

```
MLME-SYNC.request      (
    ChannelInfo,
    TrackBeacon
)
```

The primitive parameters are defined in Table 10-3.

Table 10-3—MLME-SYNC.request parameters

Name	Type	Valid range	Description
ChannelInfo	Channel information structure as defined in 11.1.3.1	Any valid channel	The channel on which to attempt coordinator synchronization.
TrackBeacon	Boolean	TRUE, FALSE	TRUE if the MLME is to synchronize with the next beacon and attempts to track all future beacons. FALSE if the MLME is to synchronize with only the next beacon.

When the MLME-SYNC.request primitive is received, the MLME will first set *phyCurrentChannelInfo* equal to the value of the ChannelInfo parameter. If the TrackBeacon parameter is equal to TRUE, the MLME will track the beacon, i.e., enable its receiver just before the expected time of each beacon so that the beacon frame can be processed. If the TrackBeacon parameter is equal to FALSE, the MLME will locate the beacon but not continue to track it.

If this primitive is received by the MLME while it is currently tracking the beacon, the MLME will not discard the primitive, but will treat it as a new synchronization request.

10.2.10.3 MLME-SYNC-LOSS.indication

The MLME-SYNC-LOSS.indication primitive indicates the loss of synchronization with a coordinator.

The semantics of this primitive are as follows:

```
MLME-SYNC-LOSS.indication      (
    LossReason,
    PanId,
    ChannelInfo,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-4.

The MLME-SYNC-LOSS.indication primitive is generated by the MLME of a device and issued to its next higher layer in the event of a loss of synchronization with the coordinator. It is also generated by the MLME of the PAN coordinator and issued to its next higher layer in the event of either a PAN ID conflict or an overlap between the outgoing superframe and the incoming superframe, as described in 10.2.2.5.

Table 10-4—MLME-SYNC-LOSS.indication parameters

Name	Type	Valid range	Description
LossReason	Enumeration	PAN_ID_CONFLICT, REALIGNMENT, BEACON_LOST, SUPERFRAME_OVERLAP	The reason that synchronization was lost.
PanId	Integer	0x0000–0xffff	The PAN ID with which the device lost synchronization or to which it was realigned.
ChannelInfo	Channel information structure as defined in 11.1.3.1	Any valid channel	The channel on which the device lost synchronization or to which it was realigned.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

The LossReason parameter indicates the reason why the primitive was issued. Values for the LossReason parameter are as follows:

- PAN_ID_CONFLICT: The device has detected a PAN ID conflict and has communicated it to the PAN coordinator or the PAN coordinator has received a PAN ID Conflict Notification command regarding a device that is associated with it, as described in 10.17.
- REALIGNMENT: The device has received the Coordinator Realignment command from the coordinator through which it is associated, and the MLME was not carrying out an orphan scan, as described in 10.20.
- BEACON_LOST: The device has missed too many beacons, as described in 10.2.6.
- SUPERFRAME_OVERLAP: The device has received a coordinator realignment comment from its coordinator that would cause the incoming and outgoing superframes to overlap, as described in 10.2.2.5.

10.2.11 MAC constants and PIB attributes for superframe structure

Superframe structure attributes are described in Table 10-5. For explanation of dagger (†) and asterisk (*) symbols see 8.4.3.1.

Table 10-5—Superframe structure related PIB attributes

Attribute	Type	Range	Description	Default
<i>macBeaconTxTime</i>	Integer*†	0x0000000 –0xffffffff	The time that the device transmitted its last beacon frame, in symbol periods. The measurement shall be taken at the same symbol boundary within every transmitted beacon frame, the location of which is implementation specific. The precision of this value shall be a minimum of 20 bits, with the lowest four bits being the least significant.	0x0000000

Table 10-5—Superframe structure related PIB attributes (continued)

Attribute	Type	Range	Description	Default
<i>macCoordRealignSecurityParams</i>	Structure	As defined in Table 8-2.	As defined in Table 8-2.	—
<i>macSuperframeOrder</i>	Integer*†	0–15	The length of the active portion of the outgoing superframe, including the beacon frame, as defined in 10.2.	15

10.3 Timeslotted channel hopping (TSCH)

10.3.1 Overview of TSCH

In a TSCH PAN, the concept of the superframe is replaced with a slotframe. The slotframe also contains defined periods of communications between peers that are either CSMA-CA or guaranteed, but the slotframe automatically repeats based on the participating devices' shared notion of time. Unlike the superframe, slotframes and a device's assigned timeslot(s) within the slotframe can be initially communicated by beacon, but are typically configured by a higher layer as the device joins the network. Because all devices share common time and channel information, devices hop over the entire channel space to minimize the negative effects of multipath fading and interference and do so in a slotted way to avoid collisions, minimizing the need for retransmissions. Both of these features are desirable for operation in a harsh industrial environment.

TSCH PANs are topology independent and can be used in star topologies as well as partial or full mesh topologies.

10.3.2 Channel access for TSCH

10.3.2.1 TSCH CCA algorithm

When a device is operating in TSCH mode as described in 10.3.3.2, CCA can be used to promote coexistence with other users of the radio channel. For other devices in the same network, the start time of transmissions, *macTsTxOffset*, is closely aligned making intra-network collision avoidance using CCA ineffective. TSCH devices also use channel hopping, so there is no backoff period used when channel access fails.

As illustrated in Figure 10-8, when a TSCH device has a packet to transmit, it shall wait for a link to the destination device. If *TschCca* was set to ON in the *MLME-TSCH-MODE.request* primitive, the MAC requests the PHY to perform a CCA at the designated time in the timeslot, *macTsCcaOffset*, without any backoff delays.

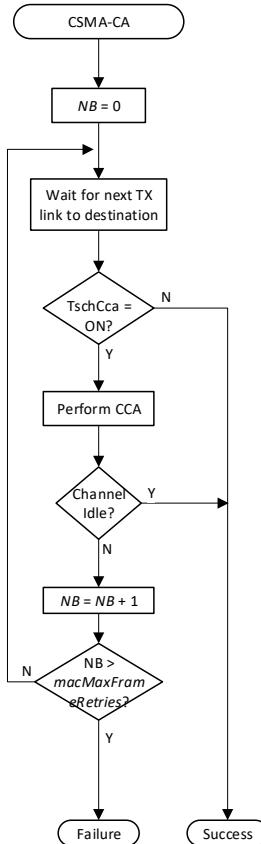


Figure 10-8—TSCH CSMA-CA algorithm

10.3.2.2 TSCH CSMA-CA retransmission algorithm

Shared links (links with the linkOptions Bitmap set to shared transmission) are intentionally assigned to more than one device for transmission. This can lead to collisions and result in a transmission failure detected by not receiving an acknowledgment. To reduce the probability of repeated collisions when the packets are retransmitted, the retransmission backoff algorithm shown in Figure 10-9 shall be implemented for shared links. BE and NB are described in 6.3.2.1. The value of NB in Figure 10-8 is carried over to Figure 10-9.

When a packet is transmitted on a shared link for which an acknowledgment is expected and none is received, the transmitting device shall invoke the TSCH retransmission procedure, which includes a backoff algorithm. Subsequent retransmissions may be in either shared links or dedicated links as retransmission occurs in the next link to the destination. The device shall use an exponential backoff mechanism analogous to that described in 6.3.2.1. The MAC sublayer shall delay for a random number in the range 0 to $(2^{BE} - 1)$ shared links (on any slotframe) before attempting a retransmission on a shared link. Retransmission on a dedicated link may occur at any time. For each successive failure on a shared link, the device shall increase the backoff exponent until the backoff exponent = $macTschMaxBe$.

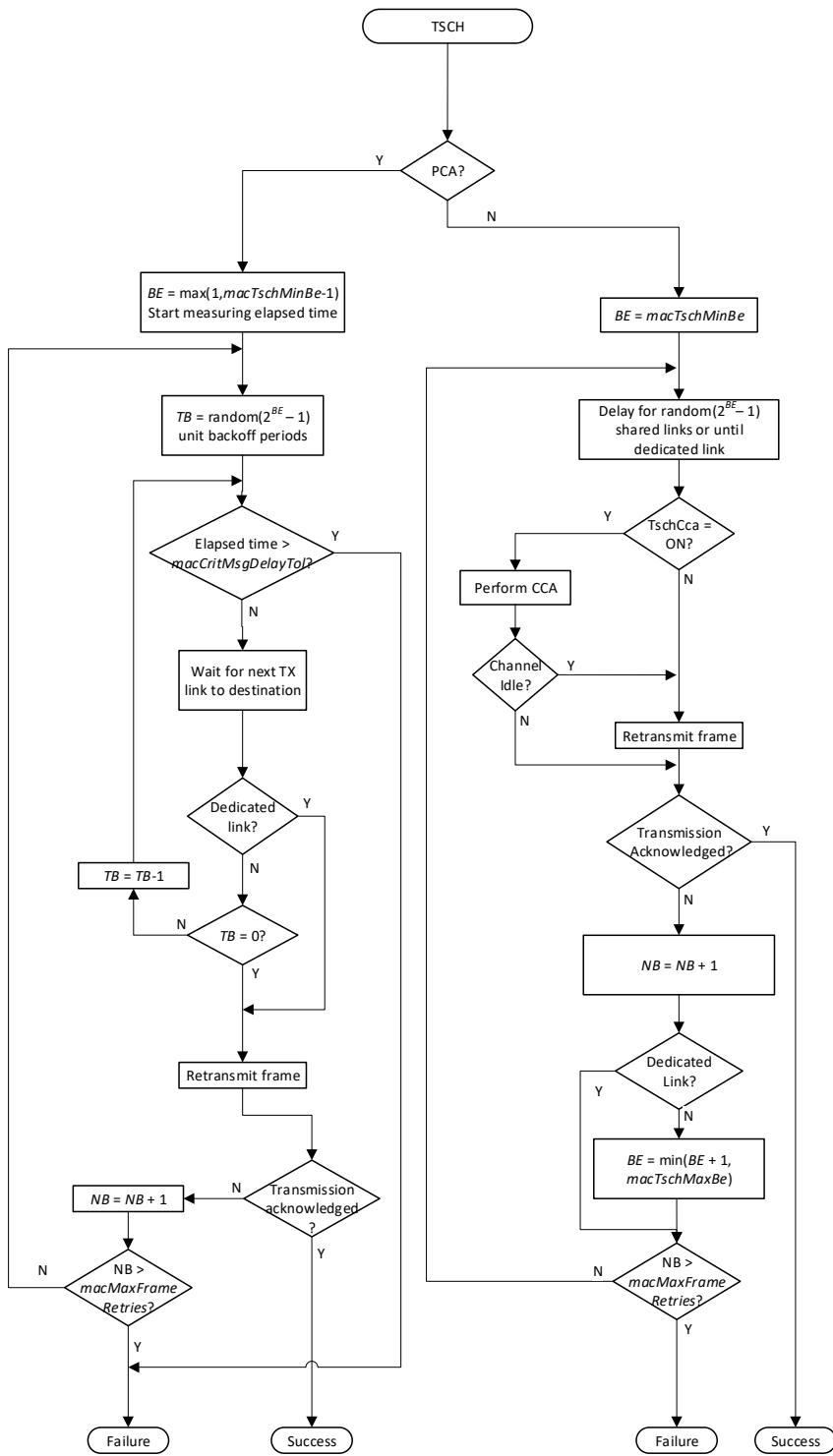


Figure 10-9—TSCH Retransmission backoff algorithm

The retransmission procedure shall follow the additional rules:

- The wait period, based on the backoff algorithm, applies only to the transmission on shared links. There is no waiting for transmission on dedicated links.
- The BE increases for each consecutive failed transmission in a shared link.
- A successful transmission resets the BE to the minimum value $macTschMinBe$.
- The BE does not change when a transmission is a failure in a dedicated link.

When the device is in TSCH mode the backoff is calculated in number of shared links. The values for $macTschMaxBe$ and $macTschMinBe$ for TSCH mode are defined in Table 10-16.

If an acknowledgment is still not received after $macMaxFrameRetries$ retransmissions, the MAC sublayer shall assume the transmission has failed and notify the next higher layer of the failure.

A device in a TSCH PAN may also use the PCA backoff method for critical event messages, as defined in 10.10.2.1.

10.3.2.3 TSCH slotframe structure

10.3.2.3.1 General

A slotframe is a collection of timeslots repeating in time. Each timeslot allows enough time for a pair of devices to exchange a frame and an acknowledgment. It is possible, although usually undesirable, to define a timeslot that is not long enough for a pair of devices to exchange a maximum length frame and an Ack frame. The number of timeslots in a given slotframe (slotframe size) determines how often each timeslot repeats, thus setting a communication schedule for nodes that use the timeslots. When a slotframe is created, it is associated with a slotframe handle ($macSlotframeHandle$) for identification. Each slotframe repeats on a cycle dependent on its length. Each timeslot is an opportunity for a device to send or receive a single frame, and optionally receive or transmit an acknowledgment to that frame. Slotframes and timeslots are configured by a higher layer.

When a timeslot has a node designated to transmit and a node designated to receive according to a $macLinkTable$ schedule as per 10.3.11, that timeslot is considered as having a link scheduled. If any of the conditions listed is absent, then there is no link scheduled for that timeslot.

10.3.2.3.2 Absolute slot number (ASN)

The total number of timeslots that has elapsed since the start of the network or an arbitrary start time determined by the PAN coordinator is called the ASN. It increments globally in the network every $macTsTimeslotLength$, as defined in Table 10-19. It may be beaconed by devices already in a TSCH PAN, allowing new devices to synchronize. It is used globally by devices in a TSCH PAN as the frame counter (thus allowing for time-dependent security) and is used to compute the channel for any given pairwise communication as described in 10.3.2.3.3.

10.3.2.3.3 Links

Figure 10-10 illustrates an example of nodes communicating in a sample three-timeslot slotframe. Nodes A and B communicate during timeslot 0, nodes B and C communicate during timeslot 1, and timeslot 2 is not being used. Every three timeslots, the schedule repeats, but note that ASN increments continuously. The pairwise assignment of a directed communication between devices for a given $macSlotframeHandle$, as defined in 10.3.11.2, in a given timeslot on a given $macTschChannelOffset$ is a link.

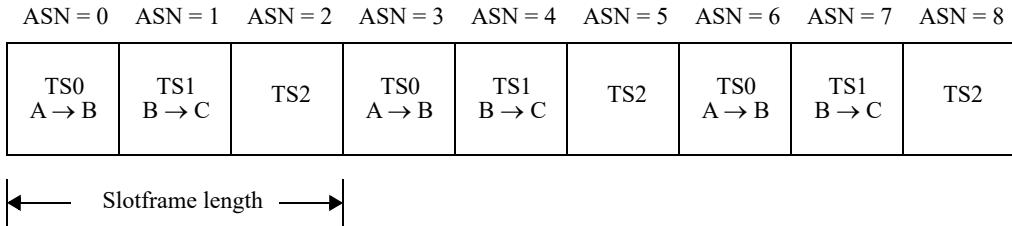


Figure 10-10—Example of a three timeslot slotframe

The physical channel, *CH*, in a link is calculated as follows:

$$CH = macHoppingSequenceList [(macAsn + macTschChannelOffset) \% macHoppingSequenceLength]$$

where $a \% b$ indicates a modulo b .

Use of a *macTschChannelOffset* allows for different channels to be used at a given *macAsn* for a given *macHoppingSequenceList*. There are *macNumberOfChannels* channel offsets that will result in a unique channel for that combination of *macAsn* and *macHoppingSequenceList*.

10.3.2.3.4 Multiple slotframes

A given network using timeslot-based access may contain several concurrent slotframes of different sizes. Multiple slotframes may be used to define a different communication schedule for various groups of nodes or to run the entire network at different duty cycles by giving some devices many active timeslots in a slotframe, and others few or none.

A network device may participate in one or more slotframes simultaneously, and not all devices need to participate in all slotframes. By configuring a network device to participate in multiple overlapping slotframes of different sizes, it is possible to establish different communication schedules and connectivity matrices that all work at the same time.

Slotframes can be added, removed, and modified while the network is running. Even though this is the case, all slotframes are aligned to timeslot boundaries, and timeslot 0 of the first repetition of every slotframe is projected back to *macAsn* = 0, which is determined by the PAN coordinator (or other network device that starts the network). Because of this, timeslots in different slotframes are always aligned, even though the beginning and end of a particular repetition of that slotframe may not be, as illustrated in Figure 10-11. When, for any given timeslot, a device has links in multiple slotframes, transmissions take precedence over receives, and lower *macSlotframeHandle* slotframes takes precedence over higher *macSlotframeHandle* slotframes.

ASN = 0 ASN = 1 ASN = 2 ASN = 3 ASN = 4 ASN = 5 ASN = 6 ASN = 7									
Slotframe 1 5 slots	TS0	TS1	TS2	TS3	TS4	TS0	TS1	TS2	...
Slotframe 2 3 slots	TS0	TS1	TS2	TS0	TS1	TS2	TS0	TS1	...

Figure 10-11—Multiple slotframes in the network

10.3.3 Starting and maintaining PANs

10.3.3.1 Realignment in a PAN

TSCH devices shall not send a Coordinator Realignment command. TSCH devices that receive a Coordinator Realignment command shall ignore the command.

10.3.3.2 TSCH PAN formation

A TSCH PAN is formed when a device, referred to as an *advertising device*, advertises the presence of the network by sending Enhanced Beacon frames upon receipt of an MLME-BEACON.request from a higher layer. In a TSCH PAN the Enhanced Beacon frames contain the following IEs:

- TSCH Synchronization IE, as described in 10.3.9.1, containing timing information so new devices can synchronize to the network.
- *Channel Hopping IE*, as described in 10.16.2.1, containing channel hopping information, as described in 10.16.1.
- *TSCH Timeslot IE*, as described in 10.3.9.3, containing timeslot information describing when to expect a frame to be transmitted and when to send an acknowledgment.
- *TSCH Slotframe and Link IE*, as described in 10.3.9.2, containing initial link and slotframe information so new devices know when to listen for transmissions from the advertising device and when they can transmit to the advertising device.

Enhanced Beacon frames in TSCH mode shall not be encrypted, but may be authenticated (i.e., security level 1, 2, or 3).

NOTE—If Enhanced Beacon frames were encrypted, the TSCH Synchronization IE used to transmit the ASN to joining devices would be encrypted as well. A joining device or a device that has lost synchronization with the network would be unable to decrypt the Enhanced Beacon frame as the current ASN is required to generate the nonce. Thus, these devices would be unable to join the network or resynchronize with the network.

The device wishing to join a TSCH network begins passively (preferred) or actively scanning for the network as the result of receiving an MLME-SCAN.request from a higher layer. Once the listening device has heard a valid Enhanced Beacon, it generates an MLME-BEACON-NOTIFY.indication to a higher layer. The higher layer may wait for additional MLME-BEACON-NOTIFY.indication primitives before selecting a TSCH network based upon the value of the Join Metric field in the TSCH Synchronization IE. The higher layer may initialize the slotframe and links contained in the Enhanced Beacon from the preferred TSCH network and switch the device into TSCH mode with an MLME-TSCH-MODE.request.

At this point the device is synchronized to the network and may optionally send an Association Request command. If the device uses association, it may request a short address. The sequence of messages exchanged to synchronize a device to the networks is shown in Figure 10-12, and the process of synchronization is described in 10.3.5.

Typically at this point the device will go through a procedure to allocate additional communication resources (slotframes and links) to the joining device. This procedure may include a security handshake to mutually authenticate the joining device, configure encryption keys, and configure routing information. The mechanism and rules for setting up these additional communication links needs to be defined in a higher layer standard.

Once synchronized and configured by a higher layer to do so, all devices that are already part of the network may send Enhanced Beacon frames announcing the presence of the network. The advertising rate and content is configured by a higher layer as appropriate to the density of devices, the desired rate of network formation, and the energy devoted to network formation.

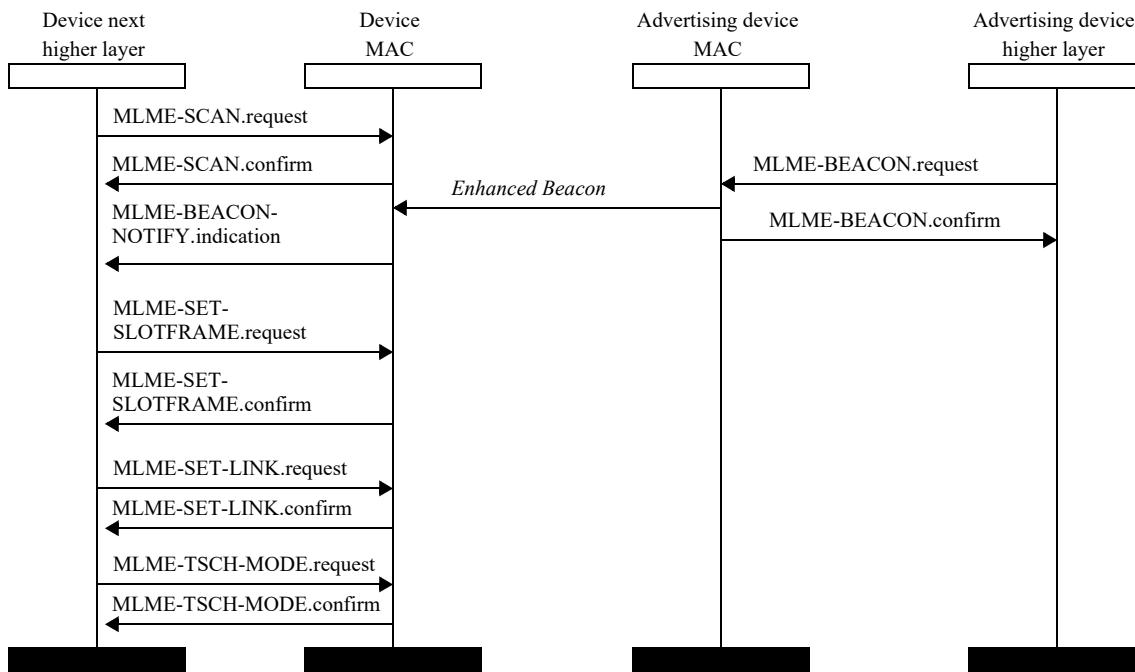


Figure 10-12—Message sequence chart for TSCH procedure to find an advertising device

After joining, the device may receive additional slotframes and links from a higher layer management entity or peer. Likewise, the device may be instructed to remove certain slotframes and links obtained from the Enhanced Beacon.

10.3.4 Association and disassociation for TSCH

10.3.4.1 Association in TSCH PAN

Association is optional for devices operating in TSCH mode.

10.3.4.2 Disassociation in TSCH PAN

When using the association in TSCH mode, additional disassociation behavior is required. A TSCH device shall disassociate from the PAN if it receives a Disassociation Notification command from either the PAN coordinator, or all of its time source neighbors, as defined in 10.3.5.

Upon determining that it should disassociate from the PAN, the device shall transmit Disassociate Notification commands to all its neighbors on any available link for *macDisconnectTime* timeslots, after which it should clear all synchronization information and leave the PAN.

10.3.5 Synchronization in TSCH PAN

10.3.5.1 General

For devices using the optional TSCH mode, initial synchronization is performed by the use of Enhanced Beacon frames, and synchronization is maintained by slotted communication with other devices in the PAN.

In a TSCH PAN, all communication happens in timeslots as described in 10.3.5.2. To remain synchronized, the devices should have the same notion of when each timeslot begins and ends, within $\pm macTsRxWait/2$. In a typical TSCH PAN, time propagates outwards from the PAN coordinator. A device shall periodically synchronize its network time to at least one other network device that is a time source neighbor. A time source neighbor is another device for which the *macLinkTimekeeping* is TRUE in the *macLinkTable* of that link. The device may also provide its network time to one or more network devices via the ASN. A higher layer may add or change time source neighbors at any time.

NOTE—A device sending Enhanced Beacons to advertise a TSCH PAN should set the Timekeeping bit in the Link Option field, as described in 10.3.9.2, for the joining devices' receive link so that joining devices can maintain time synchronization until additional time source neighbors are configured by a higher layer.

A network device may have more than one neighbor as its time source. In such cases, the device shall synchronize its time to all of the neighbors that are acting as its time source, synchronizing to the relative drift of all its time source neighbors.

Figure 10-13 shows an example of time propagation in a TSCH PAN. The arrows indicate the direction of time distribution. In this example, the PAN coordinator acts as the time source for the entire network. Device 1 synchronizes to the PAN coordinator only, and is the time source for Device 3. Device 2 synchronizes its time to both Device 1 and the PAN coordinator, and Device 4 synchronizes to the PAN coordinator, Device 2, and Device 3.

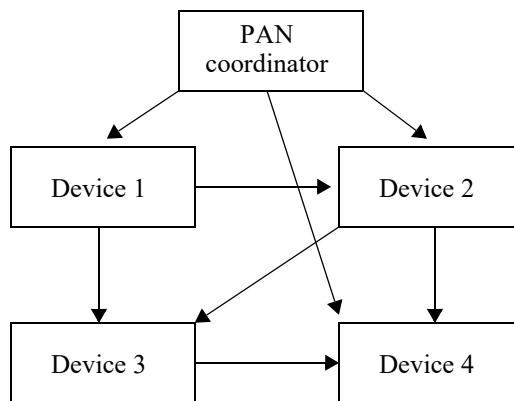


Figure 10-13—Example of possible time propagation in a TSCH PAN

Synchronization is possible whenever a device exchanges a frame with a time source neighbor. This can either come from receiving an acknowledgment with time correction information or from the arrival time of a frame from the time source neighbor. Both methods are described in 10.3.5.3.

In order to remain synchronized with the TSCH PAN, a network device shall communicate with each of its timekeeping neighbors, as defined in 10.3.10.8.

10.3.5.2 Timeslot communication

During a timeslot in a slotframe, one node typically sends a frame, and another sends back an Enh-Ack frame containing the Time Correction IE, as described in 10.3.8.1, if it successfully receives that frame. A positive acknowledgment indicates that the receiver has successfully received the frame and has taken ownership of it for further routing. A negative acknowledgment indicates that the receiver cannot accept the frame at this time, but has received it with no errors. The Time Correction IE includes timing information used by nodes to maintain network synchronization. Frames sent to a unicast node address require that a link-layer acknowledgment be sent in response during the same timeslot as shown in Figure 10-14. If an

acknowledgment is requested and not received within the timeout period, retransmission of the frame waits until the next assigned transmit timeslot to that address occurs.

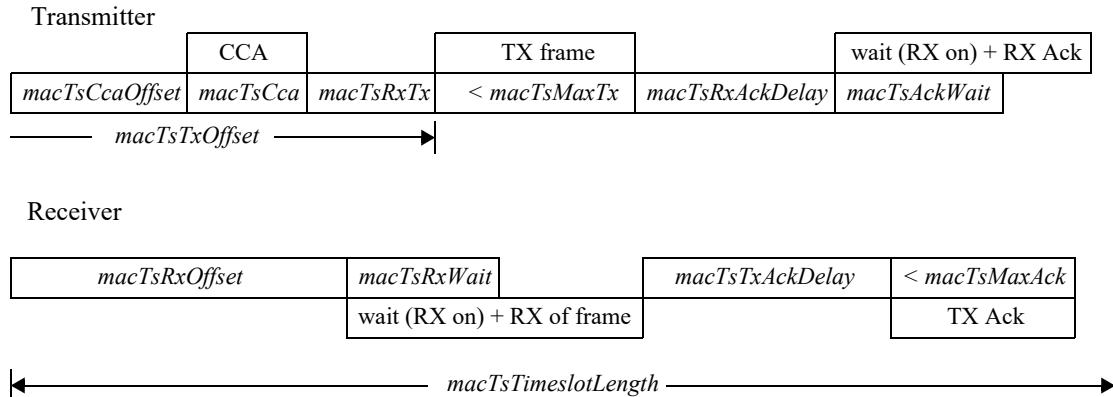


Figure 10-14—Timeslot diagram of acknowledged transmission

As shown in Figure 10-14, the timeslot starts at time $T = 0$ from the transmitting device’s perspective. The transmitter waits *macTsCcaOffset* and then performs CCA (if active). At *macTsTxOffset*, the device begins transmitting the frame. If an acknowledgment is expected, the device waits *macTsRxAckDelay* and then enables the receiver to await the acknowledgment. If the acknowledgment does not arrive within the expected time, the device may idle the radio and consider the transmission a failure. If no acknowledgment is expected, the transmitter may idle the radio after sending the frame.

On the receiver’s side, at its estimate of $T = 0$ it waits *macTsRxOffset* and then goes into receive mode for *macTsRxWait*. If the frame has not started by that time, it may idle the receiver. Otherwise, once the frame has been received, the receiver waits *macTsTxAckDelay* and then sends an acknowledgment.

The transmitter or receiver may resynchronize clocks as described in 10.3.5.3.

10.3.5.3 Node synchronization

Device-to-device synchronization is necessary to maintain connection with neighbors in a slotframe-based network. There are two methods for a device to synchronize to the network, acknowledgment-based and frame-based. Originator in this context is the device sending a frame, and receiver is the device receiving that frame and sending back an acknowledgment as is appropriate. Since timestamps are required to maintain synchronization in a TSCH PAN, all devices shall have *macTimestampSupported* set to TRUE.

Acknowledged communication provides a basic method of time synchronization through the exchange of Data frames and Ack frames. The algorithm involves the receiver calculating the delta between the expected time of frame arrival and its actual arrival, and providing that information to the transmitting node in the subsequent acknowledgment.

The acknowledgment-based synchronization algorithm can be described as follows:

- Originator sends a frame, timing the start symbol to be sent at *macTsTxOffset* according to its clock, which would correspond to *macTsRxOffset* + *macTsRxWait*/2 in the receiver’s clock if both clocks were perfectly synchronized.
- Receiver records the time from the beginning of its current slot to when it receives the start symbol of the frame, where frame is as defined in 3.1.
- Receiver calculates a time correction = *macTsRxOffset* + *macTsRxWait*/2 – arrival timestamp.

- Receiver sends back the time correction in the IE field in the corresponding Enh-Ack frame (assuming the incoming frame passes validation).
- Originator receives the acknowledgment. If the receiver node is a time source neighbor, the originator adjusts its own clock by incorporating the difference into an average of the drift to all its time source neighbors. The averaging method is implementation dependent. If the receiver is not a clock source, the time correction is ignored.

In frame-based synchronization a node may synchronize its own network clock if it receives a frame from a time source neighbor. The receiver calculates the delta between expected time of frame arrival and its actual arrival time and uses that information to adjust its own clock.

The frame-based synchronization algorithm can be described as follows:

- Receiver records the time from the beginning of its current slot to when it receives the start symbol of the frame.
- The receiver calculates a time correction = $macTsRxOffset + macTsRxWait/2$ – arrival timestamp.
- If the originator was a time source neighbor, the receiver adjusts its own clock by incorporating the information from all of its time source neighbors in an implementation-dependent manner. If the originator is not a time source neighbor, the time correction shall be ignored.

Figure 10-15 illustrates both time synchronization mechanisms. In both cases, the receiver calculates its time adjustment to either send back to the transmitting device or to use locally.

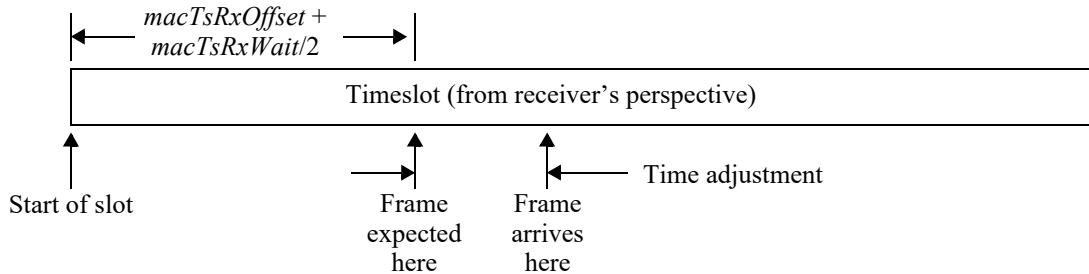


Figure 10-15—Time synchronization

10.3.6 Transmission

If security is enabled in TSCH mode, then only one frame shall be sent in a given slot to avoid the same nonce being used for more than one frame. The ASN is used in the nonce in TSCH mode.

10.3.7 Reception in TSCH

10.3.7.1 Acknowledgment

The Time Correction IE shall be used in all Enh-Ack frames if *macTschEnabled* is TRUE. When returning Time Correction IE, as described in 10.3.8.1, in the Enh-Ack frame, the receiving device may use a negative acknowledgment to indicate that the frame successfully passed FCS check, but that the MAC discarded the frame.

In TSCH mode incoming frames are acknowledged using the Enh-Ack frame as described in 7.3.3. Security of the Enh-Ack frame shall match that of the incoming frame. When operating in the TSCH mode, the Enh-Ack frame is sent at the time specified by the *macTimeslotTemplate*.

10.3.7.2 Retransmissions

If a single transmission attempt failed and the device is operating in TSCH mode, the retransmission process is defined in 10.3.2.2.

When using TSCH mode, and a frame with the Security Enabled field set to one is retransmitted, the frame shall follow the outgoing frame security procedure, as defined in 9.2.2.

NOTE—In TSCH mode, the security processing needs to be performed again because the ASN is used in the nonce and the retransmitted frame is sent in a slot with a different ASN.

10.3.8 Header IEs for TSCH

10.3.8.1 Time Correction IE

The Time Correction IE Content field shall be formatted as illustrated in Figure 10-16.

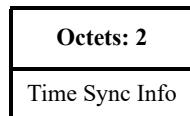


Figure 10-16—Time Correction IE Content field format

The Time Sync Info field shall specify time synchronization information and acknowledgment status. This field is constructed by taking a signed 16-bit twos-complement time correction in the range of $-2048\text{ }\mu\text{s}$ to $2047\text{ }\mu\text{s}$, ANDing it with $0xffff$, and ORing again with $0x8000$ to indicate a negative acknowledgment. This field shall be set as indicated in Table 10-6.

Table 10-6—Values of the Time Sync Info field for ACK with timing Information

Range	Description
0x000–0x7ff	Acknowledge with positive time correction in microseconds
0x800–0xffff	Acknowledge with negative time correction in microseconds
0x8000–0x87ff	Negative acknowledgment with positive time correction in microseconds
0x8800–0x8fff	Negative acknowledgment with negative time correction in microseconds

10.3.9 Nested IEs for TSCH

10.3.9.1 TSCH Synchronization IE

The TSCH Synchronization IE Content field shall be formatted as illustrated in Figure 10-17.

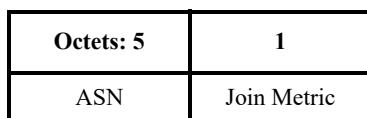


Figure 10-17—TSCH Synchronization IE Content field format

The ASN field contains the ASN corresponding to the timeslot in which the enhanced beacon is sent. The ASN is used as the Frame Counter for security operations if enabled.

The Join Metric field is an unsigned integer and shall be set to *macJoinMetric*.

10.3.9.2 TSCH Slotframe and Link IE

The TSCH Slotframe and Link IE is used in Enhanced Beacon frames to allow new devices to obtain slotframes and links for a TSCH PAN. The TSCH Slotframe and Link IE Content field shall be formatted as illustrated in Figure 10-18.

Octets: 1	variable	...	variable
Number of Slotframes	Slotframe Descriptor 1	...	Slotframe Descriptor <i>n</i>

Figure 10-18—TSCH Slotframe and Link IE Content field format

The Number of Slotframes field is set to the total number of Slotframe Descriptor fields IE.

The Slotframe Descriptor shall be formatted as illustrated in Figure 10-19.

Octets: 1	2	1	5	...	5
Slotframe Handle	Slotframe Size	Number of Links	Link Information 1	...	Link Information <i>m</i>

Figure 10-19—Slotframe Descriptor field format

The Slotframe Handle field shall be set to the *macSlotframeHandle* value from the *macSlotframeTable* for this slotframe.

The Slotframe Size field is the size of the slotframe in number of timeslots and shall be set to the corresponding *macSlotframeSize* from the *macSlotframeTable*.

The Number of Links field shall be set to the number of links that belong to the slotframe identified by the Slotframe Handle field.

The Link Information field shall be formatted as illustrated in Figure 10-20.

Octets: 2	2	1
Timeslot	Channel Offset	Link Options

Figure 10-20—Link Information field format

The Timeslot field shall be set to *macTimeslot* of the *macLinkTable*.

The Channel Offset field shall be set to *macTschChannelOffset* of the *macLinkTable*.

The Link Options field shall be formatted as illustrated in Figure 10-21.

Bits: 0	1	2	3	4	5–7
TX Link	RX Link	Shared Link	Timekeeping	Priority	Reserved

Figure 10-21—Link Options field format

The TX Link field shall be set to one if it is a TX link and shall be set to zero otherwise.

TX Shared links, indicated by the TX link field and Shared Link field both set to one, may be used by a joining device to send an Association Request command or higher layer message to the advertising device.

The RX Link field shall be set to one if the link is an RX link and shall be set to zero otherwise. RX links are used by a joining device to receive an Association Response command or higher layer message from an advertising device.

The Shared Link field shall be set to one if the link is a shared link and shall be set to zero otherwise. A shared link may be used by multiple devices to transmit, so contention shall be managed using the shared slot version of the CSMA-CA for TSCH as per Figure 6-2.

A link may be used as both a TX shared link and RX link.

The Timekeeping field shall be set to one if the link is to be used for clock synchronization and shall be set to zero otherwise. RX links shall have the Timekeeping field set to one.

The Priority field shall be set to one if the link is a priority channel access, as defined in 10.10.2.1 and Figure 10-9, and shall be set to zero otherwise.

10.3.9.3 TSCH Timeslot IE

The TSCH Timeslot IE Content field shall be formatted as illustrated in Figure 10-22. The TSCH Timeslot IE may be sent with only the Timeslot ID field to reduce the size of the beacon. Otherwise, all the fields are included. All slotframes are referred to by an ID, *macTimeslotTemplateId*, with ID = 0x00 denoting the default values for the band in use, with values given in Table 10-19.

Octets: 1	0/2	0/2	0/2	0/2	0/2	02	0/2	0/2	0/2	0/2	0/2/3	0/2/3
Timeslot ID	CCA Offset	CCA	TX Offset	RX Offset	RX Ack Delay	TX Ack Delay	RX Wait	Ack Wait	RX TX	Max Ack	Max TX	Time- slot Length

Figure 10-22—TSCH Timeslot IE Content field format

The Timeslot ID field is set to the value of *macTimeslotTemplateId* encoded as an unsigned integer.

The CCA Offset field shall be set to the value of *macTsCcaOffset* encoded as an unsigned integer.

The CCA field shall be set to *macTsCca* encoded as an unsigned integer.

The TX Offset field shall be set to *macTsTxOffset* encoded as an unsigned integer.

The RX Offset field shall be set to *macTsRxOffset* encoded as an unsigned integer.

The RX Ack Delay field shall be set to *macTsRxAckDelay* encoded as an unsigned integer.

The TX Ack Delay field shall be set to *macTsTxAckDelay* encoded as an unsigned integer.

The RX Wait field shall be set to *macTsRxWait* encoded as an unsigned integer.

The Ack Wait field shall be set to *macTsAckWait* encoded as an unsigned integer.

The RX TX field shall be set to *macTsRxTx* encoded as an unsigned integer.

The Max Ack field shall be set to *macTsMaxAck* encoded as an unsigned integer.

The length of the Max TX field and Timeslot Length field shall be the same and can be determined from the length of the IE.

The Max TX field shall be set to *macTsMaxTx* encoded as an unsigned integer.

The Timeslot Length field shall be set to *macTsTimeslotLength* encoded as an unsigned integer.

The PIB values used for this IE are defined in Table 10-19.

10.3.10 MAC management service primitives for TSCH

10.3.10.1 General

When the optional TSCH mode is implemented, the primitives listed in Table 10-7 shall be implemented.

Table 10-7—TSCH primitives

Name	Request	Indication	Response	Confirm
MLME-SET-SLOTFRAME	10.3.10.2	—	—	10.3.10.3
MLME-SET-LINK	10.3.10.4	—	—	10.3.10.5
MLME-TSCH-MODE	10.3.10.6	—	—	10.3.10.7
MLME-KEEP-ALIVE	10.3.10.8	—	—	10.3.10.9

10.3.10.2 MLME-SET-SLOTFRAME.request

The MLME-SET-SLOTFRAME.request primitive is used to add, delete, or modify a slotframe at the MAC sublayer. The SlotframeHandle is supplied by a higher layer.

The semantics of this primitive are as follows:

```
MLME-SET-SLOTFRAME.request ( 
    SlotframeHandle,
    Operation,
    Size,
    Advertise
)
```

The primitive parameters are defined in Table 10-8.

Table 10-8—MLME-SET-SLOTFRAME.request parameters

Name	Type	Valid range	Description
SlotframeHandle	Integer	0x00–0xff	Unique identifier of the slotframe.
Operation	Enumeration	ADD, DELETE, MODIFY	Operation to perform on the slotframe.
Size	Integer	0x0000–0xffff	Number of timeslots in the new slotframe.
Advertise	Boolean	TRUE, FALSE	If TRUE, this Slotframe shall be advertised in Enhanced Beacon frames using the TSCH Slotframe and Link IE. If FALSE, this slotframe shall be added locally only.

On receipt of an MLME-SET-SLOTFRAME.request, the MLME shall verify the parameters passed with the primitive. If the requested operation is set to ADD, the MLME shall attempt to add an entry into the *macSlotframeTable*. A *macSlotframeTable* entry shall be stored for each slotframe. If the requested operation is set to DELETE, all parameters except SlotframeHandle and operation shall be ignored, and the slotframe record shall be deleted from the *macSlotframeTable*. If there are links in the slotframe that are being deleted, the links shall be deleted from the MAC layer. If the device is in the middle of using a link in the slotframe that is being updated or deleted, the update shall be postponed until after the link operation completes either through a successful unacknowledged transmission, timeout for receipt of an expected acknowledgment, receipt of an invalid or unacknowledged frame, or transmission of an acknowledgment upon receipt of a valid frame. If the requested operation is MODIFY, the MAC shall attempt to update an existing slotframe record in the table.

10.3.10.3 MLME-SET-SLOTFRAME.confirm

The MLME-SET-SLOTFRAME.confirm primitive reports the results of the MLME-SET-SLOTFRAME.request primitive. The SlotframeHandle is that which was supplied by a higher layer in the prior invocation of the MLME-SET-SLOTFRAME.request primitive.

The semantics of this primitive are as follows:

```
MLME-SET-SLOTFRAME.confirm ( 
    SlotframeHandle,
    Status
)
```

The primitive parameters are defined in Table 10-9.

Table 10-9—MLME-SET-SLOTFRAME.confirm parameters

Name	Type	Valid range	Description
Slotframe Handle	Integer	0x00–0xff	Unique identifier of the slotframe to be added, deleted, or modified.
Status	Enumeration	SUCCESS, SLOTFRAME_NOT_FOUND, MAX_SLOTFRAMES_EXCEEDED, also see 8.2.2	Indicates results of the MLME-SET-SLOTFRAME.request.

The MLME-SET-SLOTFRAME.confirm primitive is generated by the MLME when the MLME-SET-SLOTFRAME.request is completed.

If any of the arguments fail a range check, the Status shall be INVALID_PARAMETER. If a new slotframe is being added and the *macSlotframeTable* is already full, the Status shall be MAX_SLOTFRAMES_EXCEEDED. If an update or deletion is being requested and the corresponding slotframe cannot be found, the Status shall be SLOTFRAME_NOT_FOUND. If an add is being requested with a SlotframeHandle corresponding to an existing slotframe, the Status shall be INVALID_PARAMETER. Otherwise the Status code shall be set to SUCCESS.

10.3.10.4 MLME-SET-LINK.request

The MLME-SET-LINK.request primitive requests to add a new link, or delete or modify an existing link at the MAC sublayer.

The semantics of this primitive are as follows:

```
MLME-SET-LINK.request      (
    Operation,
    LinkHandle,
    SlotframeHandle,
    Timeslot,
    ChannelOffset,
    TxLink,
    RxLink,
    SharedLink,
    TimekeepingLink,
    PriorityLink,
    LinkType,
    NodeAddrMode,
    NodeAddr,
    Advertise
)
```

The primitive parameters are defined in Table 10-10.

MLME-SET-LINK.request primitive can be used by the device management layer to add, delete, or modify a link in a slotframe.

When Operation is set to ADD_LINK, the MAC layer shall attempt to add the link to a new *macLinkTable* associated with the indicated slotframe. When Operation is set to DELETE_LINK, all parameters except LinkHandle and SlotframeHandle shall be ignored, and the indicated link shall be deleted from the associated *macLinkTable*. When Operation is set to MODIFY_LINK, the MAC layer shall attempt to update

Table 10-10—MLME-SET-LINK.request parameters

Name	Type	Valid range	Description
Operation	Enumeration	ADD_LINK, DELETE_LINK, MODIFY_LINK	Type of link management operation to be performed.
LinkHandle	Integer	0x0000–0xffff	Unique identifier, local to specified slotframe, for the link, as described in Table 10-18.
SlotframeHandle	Integer	0x00–0xff	The slotframe handle of the slotframe to which the link is associated.
Timeslot	Integer	0x0000–0xffff	Timeslot of the link to be added, as described in 10.3.2.3.
ChannelOffset	Integer	As defined in 10.3.2.3.3	The Channel offset of the link.
TxLink	Boolean	TRUE, FALSE	Set to TRUE if the link is a TX link; otherwise, set to FALSE.
RxLink	Boolean	TRUE, FALSE	Set to TRUE if the link is an RX link; otherwise, set to FALSE.
SharedLink	Boolean	TRUE, FALSE	Set to TRUE if the link is a shared link; otherwise, set to FALSE.
TimekeepingLink	Boolean	TRUE, FALSE	Set to TRUE if the link is to be used for clock synchronization, as described 10.3.5; otherwise, set to FALSE.
PriorityLink	Boolean	TRUE, FALSE	Set to TRUE if the link is to be used only for high priority traffic, as described 10.3.2.1; otherwise, set to FALSE.
LinkType	Enumeration	ADVERTISING, NORMAL	Set to ADVERTISING if the link is to be used to advertise the network, otherwise set to NORMAL.
NodeAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the neighbor device connected to the link.
NodeAddr	Short address or extended address	As specified by NodeAddrMode	Address of neighbor device connected by the link.
Advertise	Boolean	TRUE, FALSE	If TRUE, this Link shall be advertised in Enhanced beacon frames using the TSCH Slotframe and Link IE. If FALSE, this Link shall be added locally only.

the indicated link. If the link is currently in use, the delete or modify operation shall be postponed until the link operation completes, either through a successful unacknowledged transmission, timeout for receipt of an expected acknowledgment, receipt of an invalid or unacknowledged frame, or transmission of an acknowledgment upon receipt of a valid frame. Upon completion, the result of the operation shall be reported through the corresponding MLME-SET-LINK.confirm primitive.

If TxLink is TRUE and SharedLink is TRUE, then the device shall back off according to the method described in 10.3.2.1.

If TimekeepingLink is TRUE and RxLink is TRUE, then the neighbor specified by NodeAddr may be used for timing synchronization.

If LinkType is set to ADVERTISE, the links may be used to send Enhanced Beacon frames as the result of the MAC receiving an MLME-BEACON.request.

10.3.10.5 MLME-SET-LINK.confirm

The MLME-SET-LINK.confirm primitive indicates the result of add, delete, or modify link operation. The LinkHandle and SlotframeHandle parameter values are those that were supplied by a higher layer in the prior invocation of the MLME-SET-LINK.request primitive.

The semantics of this primitive are as follows:

```
MLME-SET-LINK.confirm      (
    LinkHandle,
    SlotframeHandle,
    Status
)
```

The primitive parameters are defined in Table 10-11.

Table 10-11—MLME-SET-LINK.confirm parameters

Name	Type	Valid range	Description
LinkHandle	Integer	0x0000–0xffff	Unique identifier, local to specified slotframe, for the link, as described in Table 10-18.
SlotframeHandle	Integer	0x00–0xff	The slotframe handle of the slotframe to which the link is associated.
Status	Enumeration	SUCCESS, UNKNOWN_LINK, MAX_LINKS_EXCEEDED, see also 8.2.2	Result of the request operation.

The Status of the primitive shall indicate SUCCESS if the operation completed successfully. If any of the arguments fail a range check, the Status shall be INVALID_PARAMETER. If a new link is being added and the *macLinkTable* is already full, the Status shall be MAX_LINKS_EXCEEDED. A *macLinkTable* shall be stored for each link in a slotframe. If an update or deletion is being requested and the corresponding link cannot be found, the Status shall be UNKNOWN_LINK. If an add is being requested with a LinkHandle corresponding to an existing link, the Status shall be INVALID_PARAMETER.

10.3.10.6 MLME-TSCH-MODE.request

The MLME-TSCH-MODE.request requests to put the MAC into or out of the TSCH mode.

The semantics of this primitive are as follows:

```
MLME-TSCH-MODE.request      (
    TschMode,
    TschCca
)
```

The primitive parameters are defined in Table 10-12.

Table 10-12—MLME-TSCH-MODE.request parameters

Name	Type	Valid range	Description
TschMode	Enumeration	ON, OFF	Used to indicate if the TSCH mode is to be started or stopped.
TschCca	Enumeration	ON, OFF	Used to indicate that CCA is to be used for transmission.

The MLME-TSCH-MODE.request may be generated by a higher layer after the device has received advertisements from the network and is synchronized to a network, i.e., in response to an MLME-BEACON-NOTIFY.indication.

Upon receipt of the request with TschMode set to ON, the MAC shall start operating its TSCH state machine using slotframes and links already contained in its *macSlotframeTable* and *macLinkTable* MAC PIB attributes. To successfully complete this request, the device shall already be synchronized to a network. The MAC shall stop using slotframes and links upon receipt of the request with TschMode set to off. The communication in non-TSCH mode shall use security keys that are different from the ones used by the TSCH mode.

10.3.10.7 MLME-TSCH-MODE.confirm

The MLME-TSCH-MODE.confirm primitive reports the result of the MLME-TSCH-MODE.request primitive.

The semantics of this primitive are as follows:

```
MLME-TSCH-MODE.confirm      (
    TschMode,
    Status
)
```

The primitive parameters are defined in Table 10-13.

Table 10-13—MLME-TSCH-MODE.confirm parameters

Name	Type	Valid range	Description
TschMode	Enumeration	ON, OFF	Used to indicate if the TSCH mode was started or stopped.
Status	Enumeration	SUCCESS, NO_SYNC	Indicates results of the MLME-TSCH-MODE.request.

The MLME-TSCH-MODE.confirm primitive is generated by the MAC layer to indicate completion of the corresponding request. If the corresponding request was to turn on its TSCH state machine, but the MAC layer has not been synchronized to a network, the Status shall be NO_SYNC. Otherwise, the Status shall be SUCCESS.

If the corresponding request was to turn off its TSCH state machine, the Status shall be SUCCESS, and the MAC layer shall stop its TSCH state machine if in use.

10.3.10.8 MLME-KEEP-ALIVE.request

The MLME-KEEP-ALIVE.request primitive requests that frames be sent to a device with a minimum period.

The semantics of this primitive are as follows:

```
MLME-KEEP-ALIVE.request      (
    DstAddr,
    DstAddrMode,
    KeepAlivePeriod
)
```

The primitive parameters are defined in Table 10-14.

Table 10-14—MLME-KEEP-ALIVE.request parameters

Name	Type	Valid range	Description
DstAddr	Short address or extended address	As specified by the DstAddrMode parameter	Address of the neighbor device with which to maintain timing.
DstAddrMode	Enumeration	SHORT, EXTENDED	The destination addressing mode of the device to monitor.
KeepAlivePeriod	Integer	0x0001–0xffff	Period in timeslots after which a frame is sent if no frames have been sent to DstAddr.

Upon receipt of the request, the MAC layer shall monitor for frames sent to the destination node specified in the DstAddr parameter. If no frame is sent to the destination node in KeepAlivePeriod, the MAC shall send a Data frame with no payload and the AR field set to request acknowledgment to its time source neighbor and use the resulting Enh-Ack frame to perform acknowledgment-based synchronization.

10.3.10.9 MLME-KEEP-ALIVE.confirm

The MLME-KEEP-ALIVE.confirm primitive reports the results of a request that frames be sent to a device with a minimum period.

The semantics of this primitive are as follows:

```
MLME-KEEP-ALIVE.confirm      (
    Status
)
```

The primitive parameter is defined in Table 10-15.

Table 10-15—MLME-KEEP-ALIVE.confirm parameters

Name	Type	Valid range	Description
Status	Enumeration	SUCCESS, see also 8.2.2	Indicates results of the MLME-KEEP-ALIVE.request.

The MAC layer shall generate MLME-KEEP-ALIVE.confirm to acknowledge that it received MLME-KEEP-ALIVE request. If the DstAddr of the MLME-KEEP-ALIVE.request does not exist in the device's neighbor table and is not 0xfffff, the Status of the primitive shall indicate INVALID_PARAMETER. Otherwise it shall return SUCCESS.

10.3.11 MAC constants and PIB attributes for TSCH

10.3.11.1 General

Table 10-16 contains the PIB values for TSCH.

Table 10-16—TSCH-specific MAC PIB attributes

Attribute	Type	Range	Description	Default
<i>macTschMinBe</i>	Integer	0– <i>macTschMaxBe</i>	The minimum value of the backoff exponent (BE) in the TSCH-CA algorithm, as defined in 10.3.2.2.	1
<i>macTschMaxBe</i>	Integer	3–8	The maximum value of the BE in the CSMA-CA algorithm, in the TSCH-CA algorithm, as defined in 10.3.2.2.	7
<i>macDisconnectTime</i>	Integer	0x0000–0xffff	Time (in Timeslots) to send out Disassociate frames before disconnecting.	0x00ff
<i>macJoinMetric</i>	Integer	0x00–0xff	The sum of one and the value of the Join Metric field from the TSCH Synchronization IE, 10.3.9.1, received in the Enhanced Beacon frame used by the device joining the network. If the device is an endpoint, the value shall be set to zero.	1
<i>macAsn</i>	Integer	0x0000000000–0xffffffffffff	The Absolute Slot Number, i.e., the number of slots that has elapsed since the start of the network. Used for nonce construction when security is enabled.	0x000000000000

10.3.11.2 *macSlotframeTable*

The attributes contained in the MAC PIB for *macSlotframeTable* are presented in Table 10-17. Each slotframe requires a *macSlotframeTable* to be stored.

Table 10-17—TSCH MAC PIB attributes for *macSlotframeTable*

Attribute	Type	Range	Description	Default
<i>macSlotframeHandle</i>	Integer	0x00–0xff	Identifier of the slotframe, as described in 10.3.2.3.	—
<i>macSlotframeSize</i>	Integer	0x0000–0xffff	Number of timeslots in the slotframe.	—
<i>macSlotframeAdvertise</i>	Boolean	TRUE, FALSE	If TRUE, this slotframe shall be advertised in Enhanced beacon frames using the TSCH Slotframe and Link IE. If FALSE, this Slotframe shall be added locally only.	—

10.3.11.3 *macLinkTable*

The attributes contained in the MAC PIB for *macLinkTable* are presented in Table 10-18. Each link requires a *macLinkTable* to be stored.

Table 10-18—TSCH MAC PIB attributes for *macLinkTable*

Attribute	Type	Range	Description	Default
<i>macLinkHandle</i>	Integer	0x0000–0xffff	Identifier of Link.	—
<i>macTxType</i>	Boolean	TRUE, FALSE	Set to TRUE if the link is a TX link, otherwise set to FALSE.	—
<i>macRxType</i>	Boolean	TRUE, FALSE	Set to TRUE if the link is an RX link, otherwise set to FALSE.	—
<i>macSharedType</i>	Boolean	TRUE, FALSE	Set to TRUE if the link is a shared link, otherwise set to FALSE.	—
<i>macLinkTimekeeping</i>	Boolean	TRUE, FALSE	Set to TRUE if the link is a timekeeping link, FALSE otherwise.	—
<i>macPriorityType</i>	Boolean	TRUE, FALSE	Set to TRUE if the link is to be used for high priority traffic, as described in 10.3.2.1, otherwise set to FALSE.	—
<i>macLinkType</i>	Enumeration	NORMAL, ADVERTISING	Type of link.	NORMAL
<i>macSlotframeHandle</i>	Integer	0x00–0xff	Identifier of Slotframe to which this link belongs.	—
<i>macNodeAddressMode</i>	Enumeration	SHORT, EXTENDED	Addressing mode of the neighbor device connected to the link.	—
<i>macNodeAddress</i>	Short address or extended address	As specified by <i>macNodeAddress Mode</i>	Address of the neighbor device connected to this link or the broadcast address.	—
<i>macTimeslot</i>	Integer	0x0000–0xffff	Timeslot for this link.	—

Table 10-18—TSCH MAC PIB attributes for *macLinkTable* (continued)

Attribute	Type	Range	Description	Default
<i>macTschChannelOffset</i>	Integer	0x0000–0xffff	Channel offset for this link.	—
<i>macLinkAdvertise</i>	Boolean	TRUE, FALSE	If TRUE, this link shall be advertised in Enhanced beacon frames using the TSCH Slotframe and Link IE. If FALSE, this link shall be added locally only.	—

10.3.11.4 *macTimeslotTemplate*

The attributes contained in the MAC PIB for *macTimeslotTemplate* are presented in Table 10-19.

Table 10-19—TSCH MAC PIB attributes for *macTimeslotTemplate*

Attribute	Type	Range	Description	Band defaults	
				2450 MHz	915 MHz
<i>macTimeslotTemplateId</i>	Integer	0x00–0xf0	Identifier of Timeslot Template.	0x00	0x00
<i>macTsCcaOffset</i>	Integer	0x0000–0xffff	The time between the beginning of timeslot and start of CCA operation, in μ s.	1800	1800
<i>macTsCca</i>	Integer	0x0000–0xffff	Duration of CCA, in μ s.	128	128
<i>macTsTxOffset</i>	Integer	0x0000–0xffff	The time between the beginning of the timeslot and the start of frame transmission, in μ s.	2120	2800
<i>macTsRxOffset</i>	Integer	0x0000–0xffff	Beginning of the timeslot to when the receiver shall be listening, in μ s.	1020	1800
<i>macTsRxAckDelay</i>	Integer	0x0000–0xffff	End of frame to when the transmitter shall listen for acknowledgment, in μ s.	800	800
<i>macTsTxAckDelay</i>	Integer	0x0000–0xffff	End of frame to start of acknowledgment, in μ s.	1000	1000
<i>macTsRxWait</i>	Integer	0x0000–0xffff	The time to wait for start of frame, in μ s.	2200	6000
<i>macTsRxBx</i>	Integer	0x0000–0xffff	Transmit to Receive turnaround, in μ s.	192	1000
<i>macTsMaxAck</i>	Integer	0x0000–0xffff	Transmission time to send an acknowledgment, in μ s.	2400	6000
<i>macTsMaxTx</i>	Integer	0x000000–0xffff	Transmission time to send the maximum length frame, in μ s.	4256	103040

Table 10-19—TSCH MAC PIB attributes for *macTimeslotTemplate* (continued)

Attribute	Type	Range	Description	Band defaults	
				2450 MHz	915 MHz
<i>macTsTimeslotLength</i>	Integer	0x00000–0xfffff	The total length of the timeslot including any unused time after frame transmission and acknowledgment, in μ s.	10000	120000
<i>macTsAckWait</i>	Integer	0x0000–0xffff	The minimum time to wait for the start of an acknowledgment in μ s.	400	400

10.4 Deterministic and synchronous multichannel extension (DSME)

10.4.1 DSME multi-superframe structure

PANs with DSME enabled use the DSME multi-superframe structure. The format of the DSME multi-superframe structure is defined by coordinators that periodically transmit an Enhanced Beacon frame with the DSME PAN Descriptor IE. A multi-superframe is a cycle of repeated superframes, each of which consists of an Enhanced Beacon frame, a CAP, and a CFP. An example of a multi-superframe structure is shown in Figure 10-23.

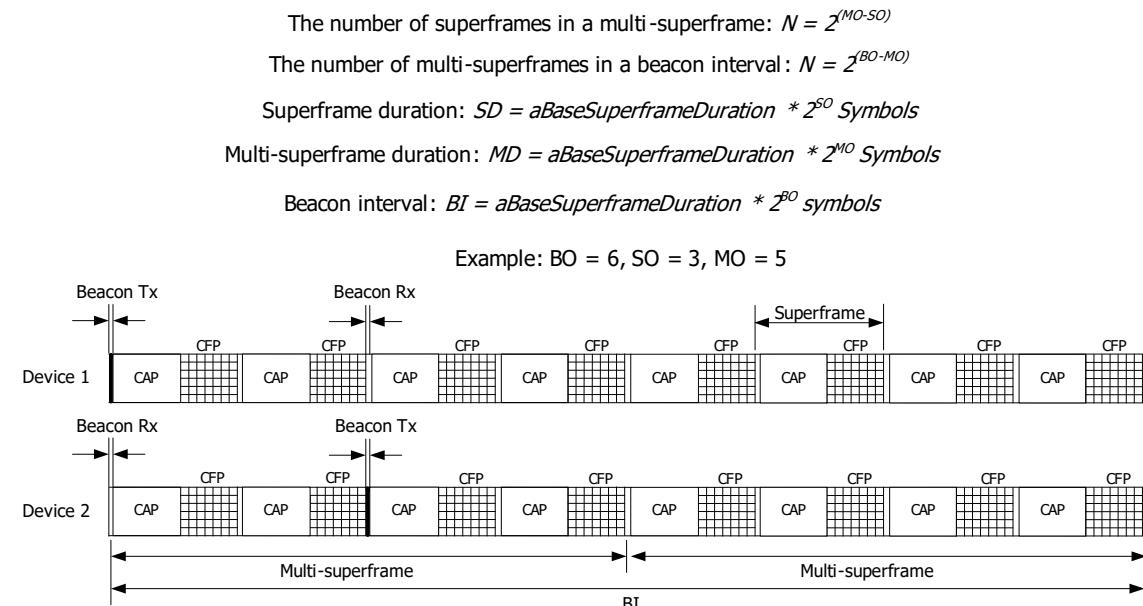


Figure 10-23—General DSME multi-superframe structure

The single common channel, the logical channel number used in the successful association, is used to transmit the Enhanced Beacon frames and the frames transmitted during the CAP. The channel diversity method, either channel adaptation or channel hopping as selected by *macChannelDiversityMode*, is applied to transmit Data frames and acknowledge frames during the CFP. Frames sent during the CFP are transmitted using the allocated channel for DSME GTS. A DSME GTS can be allocated on any of the available channels.

10.4.2 DSME command requirements

A device in a DSME-enabled PAN shall be capable of transmitting and receiving the following MAC Command frames:

- DSME Association Request command, as defined in 10.4.12.1
- DSME Association Response command, as defined in 10.4.12.2
- DSME GTS Request command, as defined in 10.4.12.3, which shall only be sent in the CAP
- DSME GTS Response command, as defined in 10.4.12.4, which shall only be sent in the CAP
- DSME GTS Notify command, as defined in 10.4.12.5, which shall only be sent in the CAP
- DSME Information Request command, as defined in 10.4.12.6
- DSME Information Response command, as defined in 10.4.12.7
- DSME Beacon Allocation Notification command, as defined in 10.4.12.8
- DSME Beacon Collision Notification command, as defined in 10.4.12.9
- DSME Link Report command, as defined in 10.4.12.10

10.4.3 DSME multi-superframe structure

A coordinator in a DSME-enabled PAN shall periodically transmit an Enhanced Beacon frame with DSME PAN Descriptor IE, as described in 10.4.11.1, to coordinate a DSME multi-superframe structure. A multi-superframe is a cycle of repeated superframes. A superframe consists of a Beacon frame, a CAP, and a CFP.

The structure of this multi-superframe is described by the values of *macBeaconOrder*, *macSuperframeOrder*, and *macMultisuperframeOrder*.

The MAC PIB attribute *macMultisuperframeOrder* describes the length of a multi-superframe. The value of *macSuperframeOrder*, *SO*, and the superframe duration, *SD*, are related as follows: for $0 \leq SO \leq BO \leq 14$, $SD = aBaseSuperframeDuration \times 2^{SO}$.

The MAC PIB attribute *macMulti superframeOrder* describes the length of a multi-superframe, which is a cycle of repeated superframes. The value of *macMultisuperframeOrder*, *MO*, and the multi-superframe duration *MD* are related as follows: for $0 \leq SO \leq MO \leq BO \leq 14$, $MD = aBaseSuperframeDuration \times 2^{MO}$. The value of *macMultisuperframeOrder* shall be ignored if *macBeaconOrder* = 15.

Each superframe shall be divided into *aNumSuperframeSlots* equally spaced slots of duration $aBaseSlotDuration \times 2^{SO}$ and is composed of three parts: an enhanced beacon, a CAP, and a CFP. Enhanced Beacon frames and other frames transmitted during CAP shall be transmitted using the channel number used in the successful association or start. Frames during CFP shall be transmitted using the assigned channel for DSME GTS.

Enhanced beacons shall be transmitted, without the use of CSMA-CA, at the start of slot 0 if *macDeferredBeaconUsed* is FALSE. The start of slot 0 is defined as the point at which the first symbol of the beacon PPDU is transmitted. If *macDeferredBeaconUsed* is TRUE, enhanced beacons shall be transmitted following the procedure described in 10.4.9.

The CAP shall commence immediately following the beacon and ends before slot 9. The CFP follows immediately after the CAP and extends to the end of the superframe. Any allocated DSME GTSs shall be located within the CFP.

An example of a multi-superframe structure is shown in Figure 10-23.

When *macExtendedDsmeEnabled* is TRUE, the Extended DSME PAN Descriptor IE shall be included in Enhanced Beacon frames that are sent every beacon interval in an Extended DSME-enabled PAN.

When *macExtendedDsmeEnabled* is TRUE, the values of the multi-superframe order, *MO*, the superframe order, *SO*, and the beacon order, *BO*, are related as follows:

$$SO \leq MO \leq [BO + \text{len(BSN)}]$$

where *len(BSN)* is 8 when the Enhanced Beacon frame contains the Sequence Number field and 0 when the Sequence Number field is not present.

Because the value of *MO* may be larger than that of *BO*, there may be multiple beacon intervals *BIs* within an *MD*. An example of a multi-superframe structure with the value of *MO* larger than that of *BO* is shown in Figure 10-24.

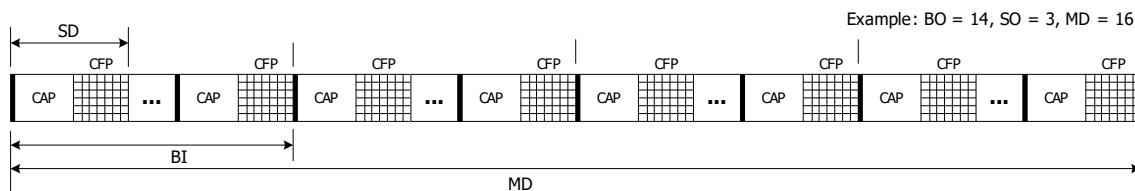


Figure 10-24—Example of DSME multi-superframe structure (*MO* > *BO*)

10.4.4 Channel diversity

10.4.4.1 General

DSME GTS service is provided in one of the two channel diversity methods, namely, channel adaptation and channel hopping.

10.4.4.2 Channel adaptation

In channel adaptation mode, the Source device may allocate DSME GTSs in a single channel or in different channels to a destination device based on the knowledge of current channel quality. If DSME GTSs in different slots in different channels are successfully allocated for a pair of a source device and a destination device, the source device shall transmit Data frames according to the scheduled timeslots and channels specified in *macDsmeAct*.

An example of the schedule of channels and DSME GTSs in channel adaptation mode is illustrated in Figure 10-25. In this example, device 1 uses channel 11 from slot 0 to 2, and then it switches to channel 13 on slot 5.

If the link quality of allocated DSME GTSs has degraded, it is recommended that the DSME GTSs should be deallocated and new DSME GTSs with better link quality should be allocated.

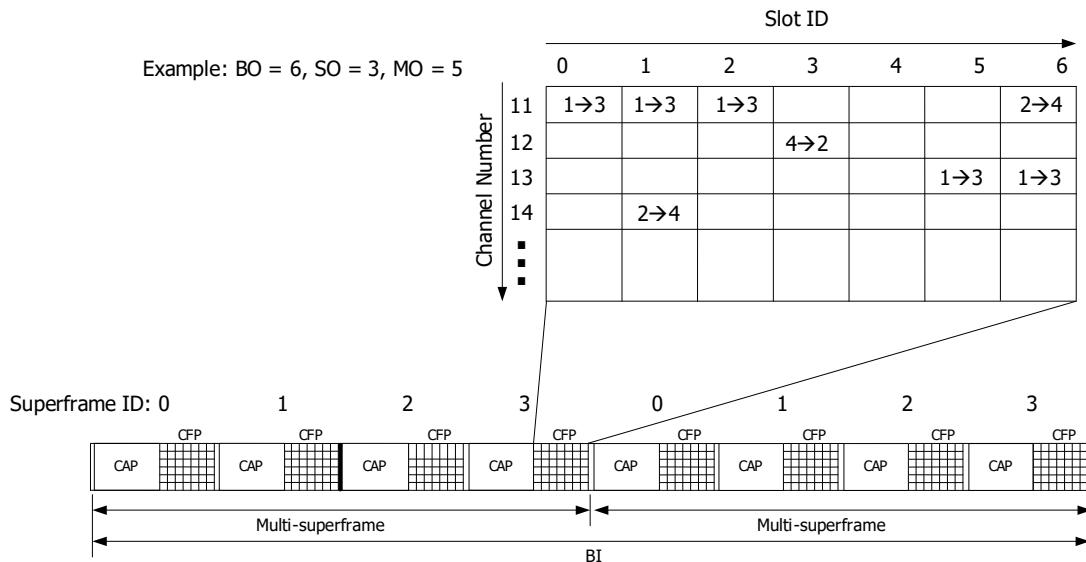


Figure 10-25—Channel usage of DSME GTSSs in channel adaptation mode

Figure 10-26 illustrates the sequence of messages necessary for DSME link report initiated by a source device. The message sequence of DSME link report initiated by a destination device is the same as the sequence initiated by a source device.

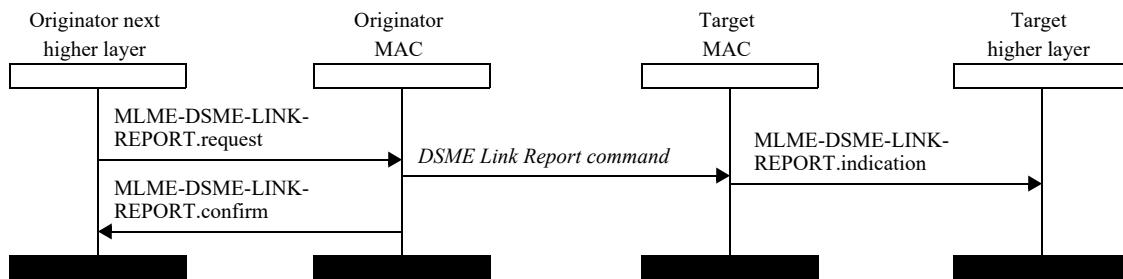


Figure 10-26—Message sequence chart for DSME link report

In channel adaptation mode, the slot allocation bitmap (SAB) sub-block is as illustrated in Figure 10-27.

DSME-GTS multi-superframe slot identifier
= (channel, timeslot)

Column = channel
Row = timeslot
0 = vacant
1 = occupied

If CAP reduction is off,
 SAB sub-block unit = 14 octets
 (7 timeslots \times 16 channels)

If CAP reduction is on,
 SAB sub-block unit = 30 octets
 (15 timeslots × 16 channels)

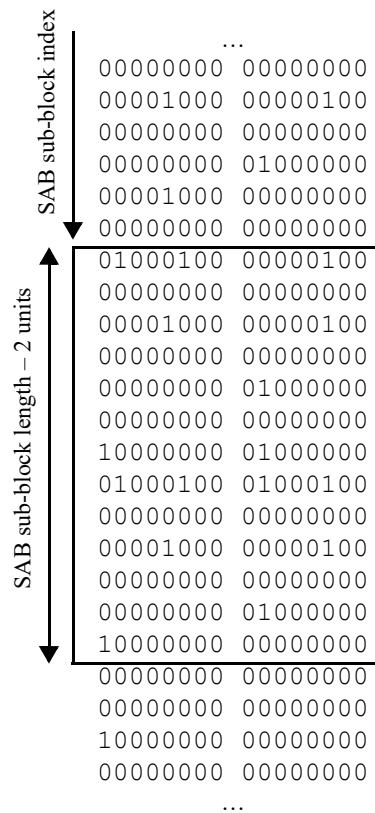


Figure 10-27—SAB sub-block in channel adaptation

10.4.4.3 Channel hopping

In channel hopping mode, each DSME GTS hops over predefined frequency channels to receive. The series of channels used at each DSME GTS is referred to as a *hopping sequence*. The same hopping sequence shall be repeated over whole DSME GTSSs.

An example of the schedule of channels and DSME GTSSs in channel hopping mode is illustrated in Figure 10-28.

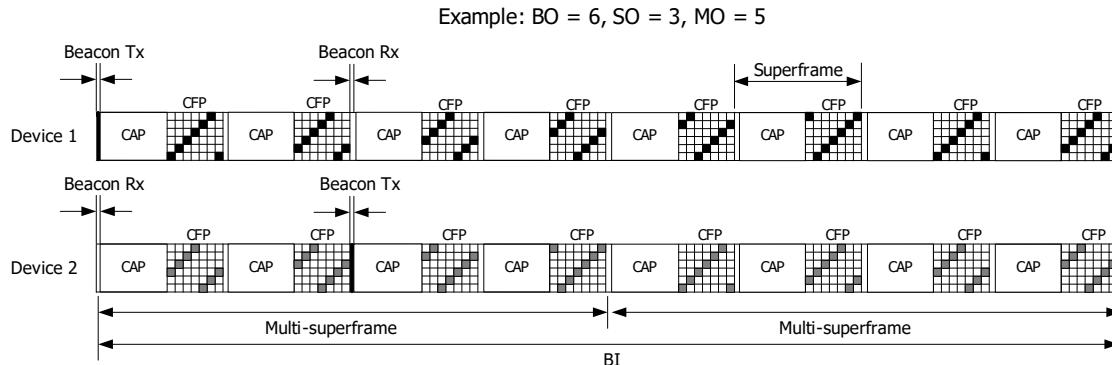


Figure 10-28—Channel usage of DSME GTSs in Channel Hopping

In this example, the hopping sequence is $\{1, 2, 3, 4, 5, 6\}$, and the channel offset values of two devices are 0 and 2, respectively. For the device with channel offset value of 0, DSME GTSs (timeslot, channel) for this device are $(1, 1), (2, 2), (3, 3), (4, 4), (5, 5), (6, 6), (7, 1), (8, 2), (9, 3)$, and so on. Similarly, for the device with channel offset value of 2, DSME slots are given as $(1, 3), (2, 4), (3, 5), (4, 6), (5, 1), (6, 2)$, and so on. The transmitting device shall switch to the channel used by the receiving device in order to send a Data frame. If the receiving device receives the Data frame successfully, it sends an Enh-Ack frame to the transmitting device on the same channel. The transmission of an Enh-Ack frame shall commence between AIFS and $(AIFS + macUnitBackoffPeriod)$ after the reception of the last symbol of the Data frame.

Channel number C at the given DSME GTS Slot ID i in SdIndex j , shall be determined as follows:

$$C(i) = \text{macHoppingSequenceList}[(j \times l + i + \text{macDsmeChannelOffset} + \text{macPanCoordinatorBsn}) \% \text{macHoppingSequenceLength}]$$

where l is 15 if macCapReduction is TRUE and SdIndex j is not zero, and 7 otherwise, $\text{macHoppingSequenceList}[m]$ represents the $(m)^{\text{th}}$ channel number in $\text{macHoppingSequenceList}$, $\text{macDsmeChannelOffset}$ is the channel offset value of the receiver device, $\text{macHoppingSequenceLength}$ is the length of Hopping Sequence and $\text{macPanCoordinatorBsn}$ is an EBSN of a PAN coordinator.

In channel hopping mode, the SAB represents the usage of corresponding DSME GTS, a bit shall be set to one if the corresponding slot is allocated to transmit or receive, or zero if the slot is available. Similarly in channel adaptation, DSME SAB sub-block index and DSME SAB sub-block length shall indicate the start position and the length of SAB sub-block. Thus, only a sub-block of whole SAB is exchanged for scheduling. This is illustrated in Figure 10-29.

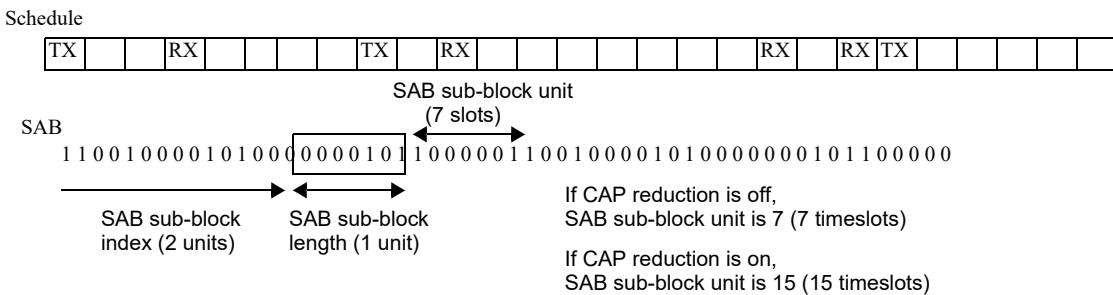


Figure 10-29—SAB sub-block in channel hopping

10.4.5 CAP reduction

If macCapReduction is TRUE, then CAP reduction shall be enabled. When the CAP reduction is enabled, the first superframe (superframe ID 0) in the multi-superframe has the CAP and all other superframes do not have a CAP.

Figure 10-30 shows an example of the multi-superframe structure when CAP reduction is enabled. As shown in Figure 10-30, every device has the CAP at the same time, which is the first superframe in a multi-superframe. The devices do not have the CAP in all other superframes.

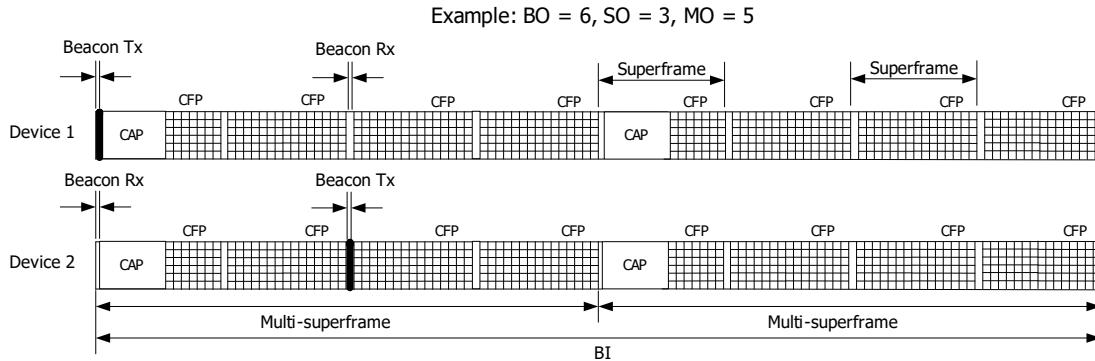


Figure 10-30—CAP reduction in DSME multi-superframe structure

10.4.6 DSME GTS allocation and management

10.4.6.1 General

DSME GTS functionality allows a DSME device to operate on the channel within a portion of the superframe that is dedicated (on the PAN) exclusively to that device. A DSME GTS shall be allocated by the destination device, and it shall be used only for communications between the source device and the destination device.

A DSME GTS allows a pair of devices to exchange a Data frame and an Ack frame. A DSME GTS shall be allocated between a pair of devices prior to its use. Allocation of a DSME GTS is initiated by a source device by transmitting a DSME GTS Request command during a CAP. The destination device determines if a DSME GTS will be allocated based on the requirements of the DSME GTS Request command and the current slot availability as described in 10.4.6.2.

DSME GTSs shall be allocated on a first-come-first-served basis, and all DSME GTSs shall be placed contiguously at the end of the superframe and after the CAP (or after the beacon slot if CAP reduction is enabled). Each DSME GTS shall be deallocated when the DSME GTS is no longer required, and a DSME GTS may be deallocated at any time by the destination device or the source device that originally requested the DSME GTS.

A Data frame transmitted in an allocated DSME GTS shall use short addressing.

The management of DSME GTSs shall be undertaken by both the destination device and the source device. To facilitate DSME GTS management, the destination device and the source device shall be able to store all the information necessary to manage DSME GTSs. For each DSME, the destination device and the source device shall be able to store its starting slot, length, and associated device address.

If a device has been allocated a DSME GTS for the data reception, it shall enable its receiver for the entirety of the DSME GTS. If a Data frame is received during a DSME GTS and an acknowledgment is requested, the destination device shall transmit the Enh-Ack frame as usual. Similarly, the source device shall be able to receive an Enh-Ack frame during the DSME GTS it requested.

10.4.6.2 DSME GTS allocation

A DSME-enabled device is instructed to request the allocation of new DSME GTSs through the MLME-DSME-GTS.request primitive with the ManagementType parameter set to ALLOCATION.

On receipt of the primitive, the device shall send a DSME GTS Request command, as described in 10.4.12.3, to the device identified by the DeviceAddress parameter of the primitive. The DSME SAB Sub-block field shall contain a bitmap of a sub-block of *macDsmeSab*. The values of the DsmeSabSubBlockIndex parameter and DsmeSabSubBlockLength parameter indicate the sub-block that shall be contained in the command.

If the device successfully transmits the DSME GTS Request command and an acknowledgment is not received, the device shall issue the MLME-DSME-GTS.confirm primitive with a Status of NO_ACK.

If no DSME GTS Response command is received within the expected time, the device shall notify the higher layer of the failure by the MLME-DSME-GTS.confirm primitive with a Status of NO_DATA.

On receipt of a DSME GTS Request command with the ManagementType set to ALLOCATION, the device shall issue an MLME-DSME-GTS.indication to the higher layer. The higher layer will make the decision on the allocation using the value of the DsmeSabSpecification parameter as the slot availability information. It is recommended that the preferred superframe ID and the preferred slot ID are considered in allocating slots. If the preferred slot is not available, the next slot may be used. Following this approach, slot allocation of a multihop flow can be allocated sequentially on each hop to reduce the end-to-end delay. After making the allocation decision, the next higher layer issues an MLME-DSME-GTS.response primitive. The DsmeSabSpecification parameter indicates the newly allocated slots.

On receipt of an MLME-DSME-GTS.response primitive with DsmeGtsStatus parameter value of APPROVED, the device shall send a DSME GTS Response command to the requesting device with the destination address set to the broadcast short address and the DSME GTS destination address set to the short address of the requesting device. The Management Type field shall be set to indicate allocation. The Dsme Gts Status field in the command shall be set to indicate approved. The DSME SAB Specification field shall be set to the same as the DsmeSabSpecification parameter of the primitive.

On receipt of an MLME-DSME-GTS.response primitive with DmseGtsStatus parameter value other than APPROVED, the device shall send a DSME GTS Response command to the requesting device. The Management Type field shall be set to allocation. The Dsme Gts Status field shall be set to either disapproved: lack of availability or disapproved: unknown GTS. The DSME SAB Specification field shall be set to the same as the DsmeSabSpecification parameter of the primitive.

On receipt of a DSME GTS Response command with management type allocation, the device shall check the DSME GTS Destination Address field of the received command.

If the DSME GTS Destination address is the same as the *macShortAddress*, the device shall inform the next higher layer of the result using MLME-DSME-GTS.confirm. If the value of the Dsme Gts Status field in the command is approved, the device shall broadcast a DSME GTS Notify command with the destination address set to the broadcast short address, and the DSME GTS destination address is set to the short address of the source device of the received command. The Management Type field shall be set to allocation. The DSME SAB Specification field shall be set to the same value as the DSME SAB Specification field in the received command. Also, the device shall update *macDsmeAct* according to the DSME SAB Specification field in the received command.

If the DSME GTS destination address of the DSME GTS Response command is not the same as the *macShortAddress*, the device shall check if the slots marked as one in the command are conflicting with the readily allocated slots in *macDsmeAct*. If there is no conflict, the device shall update *macDsmeSab* according to the DSME SAB Specification field in this command to reflect the neighbor's newly allocated DSME GTSSs. If there is a conflict, the device shall send a DSME GTS Request command with Management Type field set to duplicated allocation notification to the source device of the received command.

On receipt of a DSME GTS Notify command with management type allocation, the device shall check the DSME GTS Destination Address field of the received command. If the DSME GTS Destination address is the same as the *macShortAddress*, the device shall notify the next higher layer of the receipt of the DSME GTS Notify command using MLME-COMM-STATUS.indication. The device shall update *macDsmeAct* according the value of DSME SAB Specification field of the DSME GTS Notify command.

If a DSME GTS Notify command is not received at the destination device within the expected time, the device shall notify the higher layer of the failure by the MLME-COMM-STATUS.indication primitive with a Status of TRANSACTION_EXPIRED.

If the DSME GTS destination address of the DSME GTS Notify command is not the same as the *macShortAddress*, the device shall check if the slots marked as one in this command are conflicting with the readily allocated slots in *macDsmeAct*. If there is no conflict, the device shall update *macDsmeSab* according to the DSME SAB Specification field to reflect the neighbor's newly allocated DSME GTSSs. If there is a conflict, the device shall send a DSME GTS Request command with the Management Type field set to duplicated allocation notification to the source of the received command.

On receipt of a DSME GTS Request command indicating a DSME GTS duplicate allocation notification, the device shall deallocate the duplicated DSME GTSSs as described in 10.4.6.3.

Figure 10-31 depicts the message flow for the case in which an originator device initiates the DSME GTS allocation, deallocation, duplicated allocation notification, reduce, or restart.

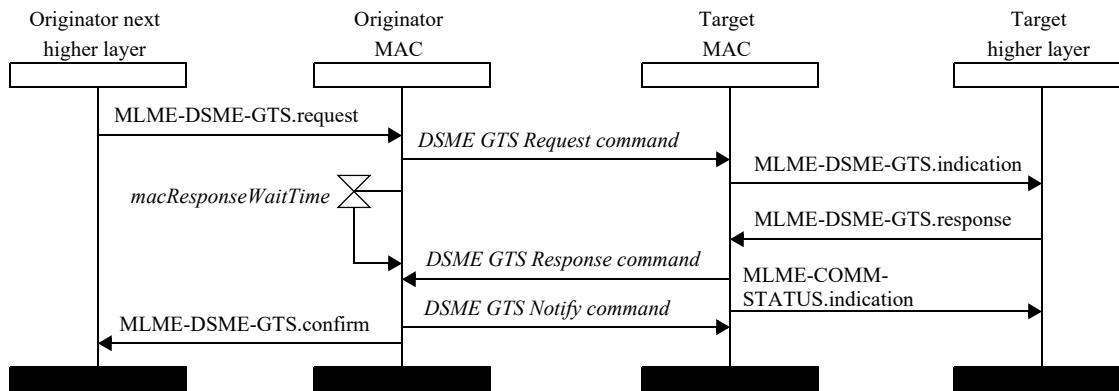


Figure 10-31—Message sequence chart for DSME GTS allocation and management

As an example of a DSME GTS allocation, consider device 3 is requesting 2 slots to transmit data to device 1. Assuming timeslot 0, channel 15 is already assigned by device 4 for transmitting data from device 4 to device 3 and channel 19 is a bad channel, then the messages would be as follows:

- 1) Device 3 sends a unicast DSME GTS Request command to device 1 with 2 slots request, Direction field set to TX, Preferred Superframe ID field set to one, and the SAB Sub-block field set as follows:

{000010010000000

0000000010000000

...

0000000010000000}

- 2) Device 1 sends a broadcast DSME GTS Reply command with the Destination Address field in the command set to that of device 3, Direction field set to TX, Superframe ID set to one, and a newly allocated SAB Sub-block field set as follows:

```
{0000000000000000
0000001000000000
0000001000000000
...
0000000000000000}
```

- 3) Device 3 sends a broadcast DSME GTS Notify command with the Destination Address field in the command set to that of device 1, the Direction field set to TX and a newly allocated SAB Sub-block field set as follows:

```
{0000000000000000
0000001000000000
0000001000000000
...
0000000000000000}
```

Devices in the DSME-enabled PAN that hear either the DSME GTS Reply command or DSME GTS Notify command will update their SAB.

Devices in a DSME-enabled PAN may be allocated DSME GTSs during the association procedure. If *macExtendedDsmeEnabled* is TRUE and a device is instructed to associate with the PAN through the MLME-ASSOCIATE.request primitive having the DsmeAssociation parameter set to TRUE, the device requests DSME GTS allocation by sending a DSME Association Request command to a coordinator with the Extended DSME GTS Allocation field present, as described in 10.4.12.1. On receipt of the DSME Association Request command, the MAC sublayer of the coordinator informs the next higher layer that DSME GTS allocation is being requested through the MLME-ASSOCIATE.indication primitive with the DsmeAssociation parameter set to TRUE. The next higher layer of the coordinator instructs the MAC sublayer to respond to the request for DSME GTS allocation through the MLME-ASSOCIATE.response primitive. Then, the MAC sublayer of the coordinator sends a DSME Association Response command to the device containing the DSME GTS allocation information described in 10.4.12.2. On receipt of the DSME Association Response command, the MAC sublayer of the device allocates a DSME GTS and reports the results to the next higher layer. The DSME association process for a device that is not tracking the beacon is shown in Figure 10-32.

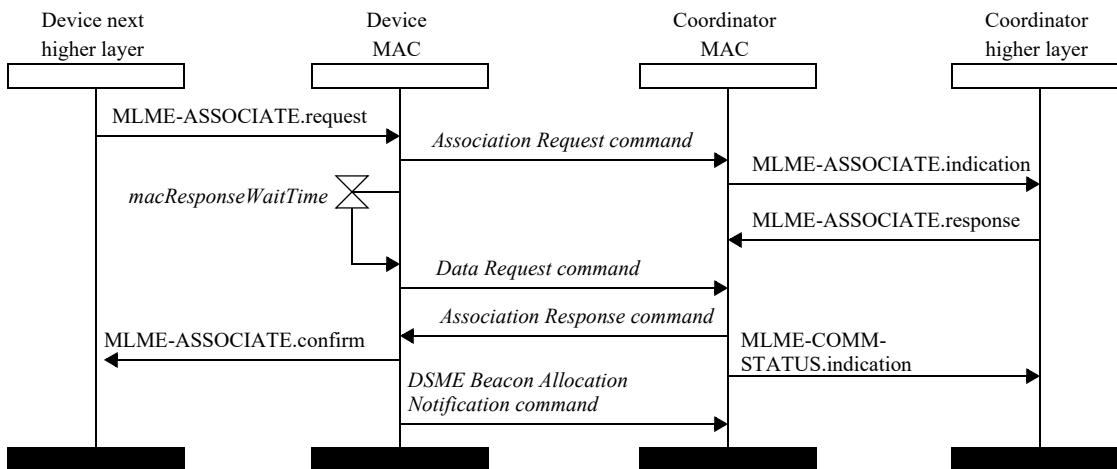


Figure 10-32—DSME association message sequence chart

10.4.6.3 DSME GTS deallocation

The DSME GTS source device is instructed to request the deallocation of an existing DSME GTS through the MLME-DSME-GTS.request primitive. The destination device may also request the deallocation of an existing DSME GTS upon the expiration of the DSME GTS. From this point onward, the DSME GTS to be deallocated shall not be used by the device, and the *macDsmeSab* and the *macDsmeAct* shall be reset accordingly.

The higher layer of the device initiates a DSME GTS deallocation by issuing the MLME-DSME-GTS.request primitive to the MAC with the ManagementType parameter set to deallocation and the DsmeSabSpecification set to indicate the DSME GTSSs to deallocate.

When a DSME GTS deallocation is due to the DSME GTS expiring, the device shall issue the MLME-DSME-GTS.indication primitive with the ManagementType parameter set to EXPIRATION.

To deallocate existing DSME GTSSs, the device shall send the DSME GTS Request command to the corresponding device. (The source or destination of which the DSME GTSSs are to be deallocated.) The destination address of the command shall be set to the address of the corresponding device. The Management Type field shall be set to deallocation, and the DSME SAB Specification field shall be set to indicate the DSME GTSSs to deallocate.

If a DSME GTS Response command with Management Type field set to deallocation is not received within the expected time, the MLME of the device shall notify the higher layer of the failure by the MLME-DSME-GTS.confirm primitive with a Status parameter set to NO_DATA.

On receipt of a DSME GTS Request command with Management Type field set to deallocation, the device shall check the DSME GTSSs specified for deallocation in the received command.

If the DSME GTSSs in the command match one or more of the allocated DSME GTSSs in *macDsmeAct*, the device shall notify the receipt of the command to the higher layer using MLME-DSME-GTS.indication. The higher layer makes the decision on the deallocation, and informs MLME of its decision using MLME-DSME-GTS.response. Then, the device shall send a DSME GTS Response command to the source device of the received command (i.e., the destination address is set to the short broadcast address, and the DSME GTS destination address is set to the short address of the source device). The Management Type field of the DSME GTS Response command shall be set to deallocation, and the Dsme Gts Status field shall be set to approved. The DSME SAB Specification field shall be set to indicate the DSME GTSSs to deallocate.

If the DSME GTSSs in the command do not match any of the allocated DSME GTSSs in *macDsmeAct*, the device shall send a DSME GTS Response command to the source device of the received command (i.e., the destination address is set to the short address of the source device, and also the DSME GTS destination address is set to the short address of the source device). The Management Type field shall be set to deallocation, and the Dsme Gts Status field shall be set to disapproved: unknown GTS. The DSME SAB Specification field shall be set to the same as the received command.

On receipt of a DSME GTS Response command with Management Type field set to deallocation, the device shall check the DSME GTS Destination Address field of the received command. If the DSME GTS Destination address is the same as the *macShortAddress*, the device shall inform the next higher layer of the result of the DSME GTS deallocation request using MLME-DSME-GTS.confirm. If the value of the Dsme Gts Status field in the command is approved, the device shall send a DSME GTS Notify command to the source device of the received command (i.e., the destination address is set to short broadcast address, and the DSME GTS destination address is set to the short address of the source device). The Management Type field of the DSME GTS Notify command shall be set to deallocation, and the DSME SAB Specification field shall be set to indicate the DSME GTSSs to deallocate.

If the DSME GTS Destination address is not the same as the *macShortAddress*, the device shall update *macDsmeSab* according to the DSME SAB Specification field in this command to reflect the neighbor's deallocated DSME GTSSs.

On receipt of a DSME GTS Notify command with Management Type field set to deallocation, the device shall check the DSME GTS Destination Address field of the received command. If the DSME GTS Destination address is the same as the *macShortAddress*, the device shall notify the next higher layer of the receipt of the DSME GTS Notify command using MLME-COMM-STATUS.indication.

If the DSME GTS Destination address is not the same as the *macShortAddress*, the device shall update *macDsmeSab* according to the DSME SAB Specification in this command to reflect the neighbor's deallocated DSME GTSSs.

10.4.6.4 DSME GTS expiration

The MLME of the device shall attempt to detect idle DSME GTSSs in *macDsmeAct*, described in Table 10-35, using the following rules:

- The MLME of the device shall perform DSME GTS deallocation when a DSME GTS has expired (i.e., a device has stopped using the DSME GTS).
- The MLME of the destination device of DSME GTS shall assume that the source device is no longer using its DSME GTS if a Data frame has not been received in the DSME GTS for *macDsmeGtsExpirationTime*.
- The MLME of the Source device of DSME GTS shall assume that the link quality is bad if an Enh-Ack frame has not been received within *macDsmeGtsExpirationTime* when the acknowledgment was requested.

10.4.6.5 DSME GTS retrieve

A DSME-enabled device needs to maintain time synchronization and DSME GTS related information in order to use DSME GTS.

If the originator device has lost synchronization before its allocated DSME GTSSs of the current superframe start, the originator device sends a DSME Information Request command to the target device. The Info Type field shall be set to the appropriate value based on the information that is being requested.

On receipt of a DSME Information Request command with Info Type field set to timestamp, the target device shall determine whether it has an allocated DSME GTS to the requesting device. If it has an allocated DSME GTS, the target device shall send a DSME Information Response command in the DSME GTS. If it does not have an allocated DSME GTS to the originator device, the target device shall ignore the request.

On receipt of a DSME Information Request command with Info Type field set to request SAB specification, the target device shall send a DSME Information Response command with the DSME SAB Specification field set according to the current allocation status of all one-hop neighborhoods of the device. The entire DSME SAB is stored in *macDsmeSab*. The DSME SAB sub-block index and the DSME SAB sub-block length indicate which part of the *macDsmeSab* shall be selected as the DSME SAB sub-block to be included in the DSME Information Response command.

On receipt of a DSME Information Request command with Info Type field set to request the PAN descriptor, the target device shall send a DSME Information Response command with the DSME PAN Descriptor.

On receipt of a DSME Information Response command containing the Timestamp field, Superframe ID field, and the Slot ID field, the originator device may use this information to retrieve synchronization and continue to use DSME GTSs.

The message sequence chart for a successful exchange of DSME information is shown in Figure 10-33.

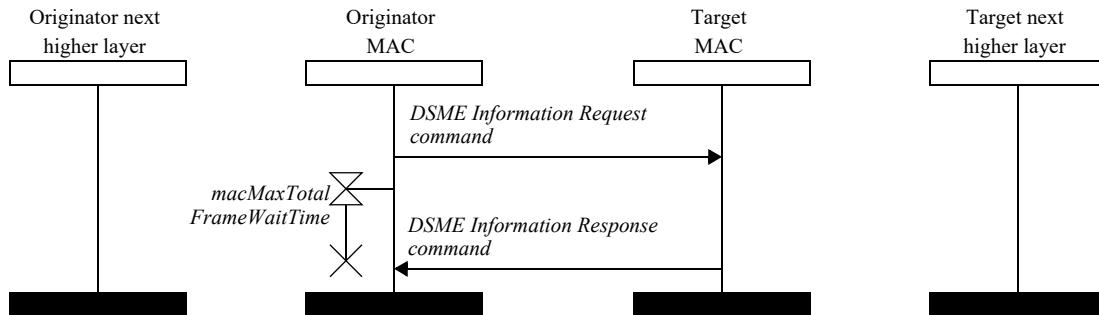


Figure 10-33—Message sequence chart for DSME information request

10.4.6.6 DSME GTS change

The procedure of DSME GTS change shall be initiated either by the MAC or by the next higher layer. The next higher layer initiates a DSME GTS change by issuing an MLME-DSME-GTS.request primitive with the ManagementType parameter set to REDUCE.

To request the change of existing DSME GTSs, the MLME of the device shall send the DSME GTS Request command to the corresponding device of the DSME GTSs. The Management Type field shall be set to either reduce or restart, and the DSME GTS SAB Specification field shall be set to indicate the DSME GTSs to change.

On receipt of a DSME GTS Request command for DSME GTS change, if the GTS exists, the device shall immediately change its DSME GTS according to the Management Type field in the received command. Then the MLME of the device shall issue the MLME-DSME-GTS.indication primitive as described in 10.4.13.2.3 to notify the next higher layer of the change. The device shall send a DSME GTS Response command to the source of the DSME GTS Request command.

If the GTS does not exist, then the device sends a DSME GTS Response command to the source of the DSME GTS Request command with the Dsme Gts Status field set to Disapproved: unknown GTS.

On receipt of the DSME GTS Response command, the MLME of the device shall issue the MLME-DSME-GTS.confirm primitive, as described in 10.4.13.2.5, with a Status parameter of SUCCESS, DsmeGtsStatus parameter copied from the Dsme Gts Status field of the DSME GTS Response command, the ManagementType parameter set to either reduce or restart, based on the value of the Management Type field in the command, and DsmeGtsSabSpecification parameter set to indicate the DSME GTSs to change.

10.4.7 Beacon scheduling

The transmission of Enhanced Beacon frames from different devices shall be scheduled using the procedure described in this subclause.

When a new device wants to join a network, it uses the MLME-SCAN.request primitive in order to initiate a channel scan over a given set of channels. It searches for all coordinators transmitting Enhanced Beacon frames within the maximum BI period. The neighboring devices (i.e., coordinators) would share their beacon schedule information by transmitting an Enhanced Beacon frame to the new device. The beacon

schedule information is expressed in a bitmap sequence that represents the schedule of Enhanced Beacon frames transmitted from all neighboring devices. The corresponding bit in the bitmap shall be set to one if a beacon is occupied in that beacon slot. The new device shall search for a vacant beacon slot from the bitmap in all the received Enhanced Beacon frames. Once the new device finds a vacant beacon slot, it uses the slot as its own beacon slot.

There can be a beacon slot collision when two or more devices are trying to compete for same beacon slot number. Figure 10-34 illustrates this circumstance; devices D and E are new devices that join the network, and these devices receive the beacon bitmap from their neighboring devices. Since device A is a common neighboring device to device D and E, there can be a collision if both new devices E and D notify the use of the same vacant beacon slot within the CAP. This happens because devices D and E are hidden from each other, and cannot listen to each other's transmission. The DSME Beacon Allocation Notification command is used to resolve this possible collision. If devices D and E send a DSME Beacon Allocation Notification command with the same SdIndex value (SdIndex of 1 in Figure 10-34), device A determines which device has notified first. Device A shall respond with the Beacon Collision Notification command to the device that has notified later.

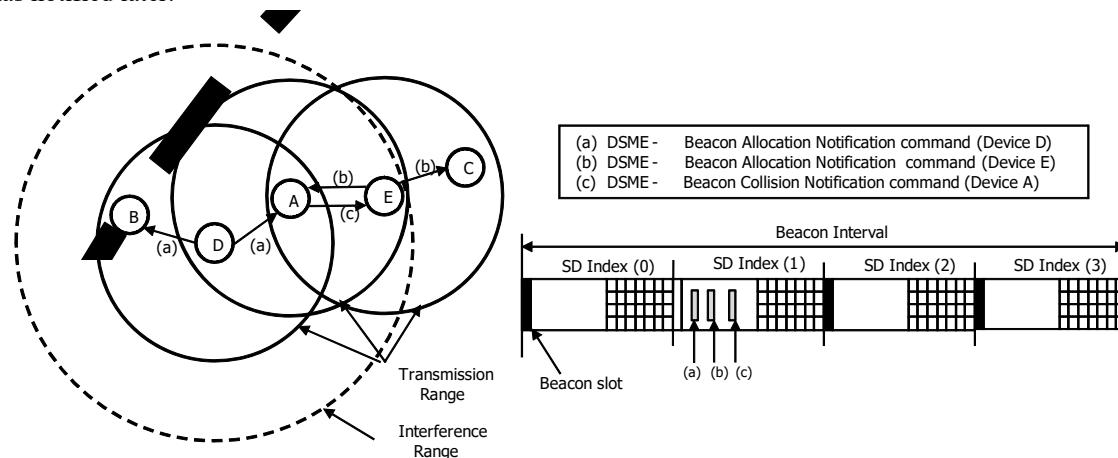


Figure 10-34—Avoidance of beacon slot allocation collision

10.4.8 Time synchronization

A new device discovers its neighboring devices via the scanning process. Upon discovering its neighbor devices, it may associate with one of them to become part of the network. The device with which the new device associates is referred to as its time synchronization parent. Since the new device tracks its time synchronization parent's Enhanced Beacon frame, it shall determine the receiving time of Enhanced Beacon frame.

Each device performs time synchronization using the values of the Timestamp fields in the Enhanced Beacon frame from its time synchronization parent in order to maintain global time synchronization in the PAN. As shown in Figure 10-35, a device locates the start time of the superframe using the value of the Beacon Timestamp field in the Enhanced Beacon frame. The device knows when the Enhanced Beacon frame is actually transmitted from the time synchronization parent using value of the Beacon Offset Timestamp field. The difference in timestamp values reflects time delay due to CCA or processing time at PHY to transmit a frame. A device that has received the Enhanced Beacon frame calculates the actual reception time considering the value of the Beacon Offset Timestamp field, and then resets its local time accordingly. The PAN coordinator does not reset its local time according to the received Enhanced Beacon frame since the PAN coordinator does not have the time synchronization parent device.

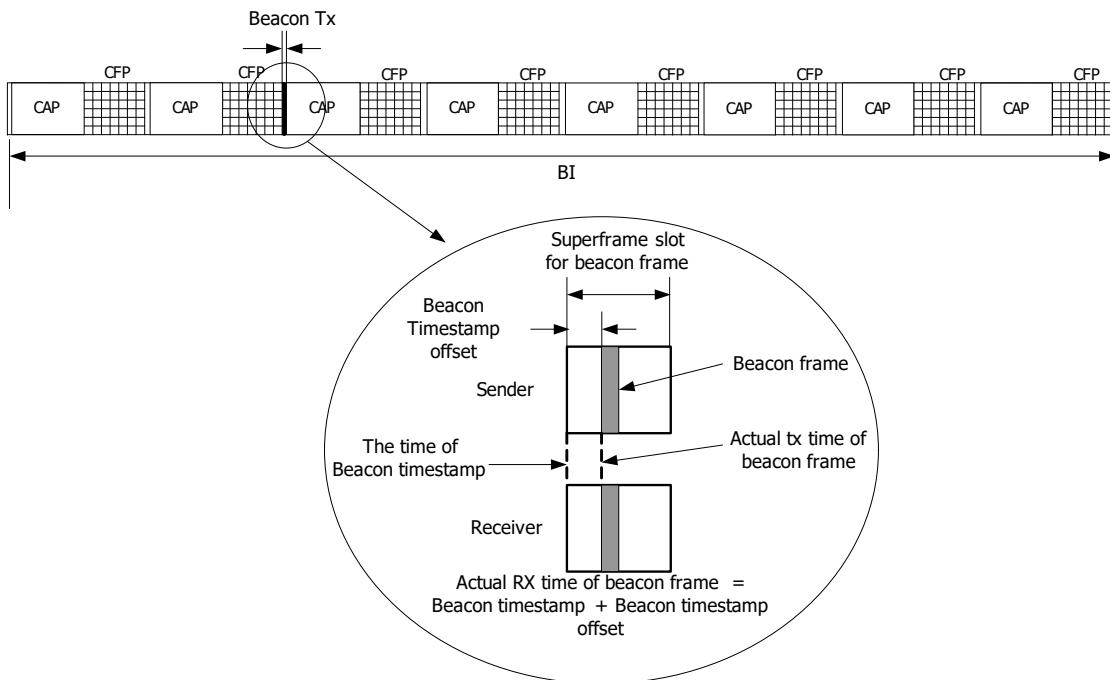


Figure 10-35—Time synchronization in a DSME-enabled PAN

10.4.9 Deferred beacon

Generally in a PAN using superframe structure, Beacon frames are transmitted without CCA or backoff. However, Beacon frames can experience a collision due to the interference from inside or outside of the PAN. In such an environment, a coordinator may use a deferred beacon to avoid the collision problem and improve the reliability of the beacon transmission. If a coordinator is instructed to use the deferred beacon, a coordinator shall set the Deferred Beacon field in its Enhanced Beacon frames to indicate deferred beacons. Then, the coordinator shall use CCA before sending an Enhanced Beacon frame. If CCA confirms the clear channel, the coordinator shall send the beacon. The Beacon Timestamp field of the Enhanced Beacon frame shall be set to the start time of the superframe. The Beacon Offset Timestamp field shall be set to the amount of time that is delayed due to CCA.

10.4.10 Passive channel scan

The Channel Hopping Specification field in the received Enhanced Beacon frame shall be included in the PayloadIeList of the PanDescriptor, and this value is sent to the next higher layer via the MLME-SCAN.confirm primitive. The value of the Channel Offset field in the received beacon shall update the value of *macChannelOffsetBitmap*. For instance, if ChannelOffset is set to 0x01, the value of *macChannelOffsetBitmap* corresponding channel shall be set to one. Thus, the value of *macChannelOffsetBitmap* shall represent whether the channel offset value is used among one hop neighbor devices.

10.4.11 Header IEs for DSME

10.4.11.1 DSME PAN Descriptor IE

The DSME PAN Descriptor IE shall be included in enhanced beacons that are sent every beacon interval in a DSME-enabled PAN.

The DSME PAN Descriptor IE Content field shall be formatted as illustrated in Figure 10-36.

Octets: 2	variable	1	8	variable	variable
Superframe Specification	Pending Address	DSME Superframe Specification	Time Synchronization Specification	Beacon Bitmap	Channel Hopping Specification

Figure 10-36—DSME PAN Descriptor IE Content field format

The Superframe Specification field is described in 7.3.1.4.

The Pending Address field is described in 7.3.1.6.

The DSME Superframe Specification field shall be formatted as illustrated in Figure 10-37.

Bits: 0–3	4	5	6	7
Multi-superframe Order	Channel Diversity Mode	Reserved	CAP Reduction	Deferred Beacon

Figure 10-37—DSME Superframe Specification field format

The Multi-superframe Order field shall specify the length of time during which a group of superframes that is considered as one multi-superframe lasts (i.e., receiver enabled). See 10.4.3 for an explanation of the relationship between the multi-superframe order and the multi-superframe duration.

The Channel Diversity Mode field shall indicate the type of channel diversity. If this value is zero, the DSME-enabled PAN operates on channel adaptation mode. If this value is one, the DSME-enabled PAN operates on channel hopping mode.

The CAP Reduction field shall be set to one if the CAP reduction is enabled; otherwise, the CAP Reduction field shall be set to zero.

The Deferred Beacon shall be set to one if the device uses CCA before transmitting a Beacon frame. Otherwise, the bit shall be set to zero if the device shall not use CCA before transmitting beacons.

The Time Synchronization Specification field shall be formatted as illustrated in Figure 10-38.

Octets: 6	2
Beacon Timestamp	Beacon Offset Timestamp

Figure 10-38—Format of the Time Synchronization Specification field

The Beacon Timestamp field shall specify the start time of the beacon slot in which the beacon was transmitted in units of microseconds.

The Beacon Offset Timestamp field specifies that the time difference between the start time of a superframe and the actual time of transmitting a Beacon frame. It reflects the delay due to CCA or processing time of the PHY to transmit a frame.

The Beacon Bitmap field shall be formatted as illustrated in Figure 10-39.

Octets: 2	2	variable
SD Index	SD Bitmap Length	SD Bitmap

Figure 10-39—Format of the Beacon Bitmap field

The SD Index field specifies the index of the current *SD* in a beacon interval. The superframe in which the PAN coordinator sends its beacons serves as the reference point (SD Index 0). When this field is contained in an enhanced beacon, this field specifies the index of the superframe that is allocated to the Source device of the beacon for beacon transmission.

The SD Bitmap Length field shall be set to the length of SD Bitmap field in octets.

The SD Bitmap field contains a bitmap indicating the Beacon frame allocation information of all $2^{(BO-SO)}$ superframes within one beacon interval. Each corresponding bit in the bitmap shall be set to one if a beacon of a neighbor device is allocated in that *SD*; otherwise, it is set to zero. It should be noted that the length of the Beacon frame allocation information bitmap, $2^{(BO-SO)}$, may be different than the value of the SD Bitmap Length field since the SD Bitmap Length field is represented in octets. In this case, the value of the SD Bitmap Length field shall be chosen to be the smallest integer that is greater than the length of this bitmap, and those bits after the first $2^{(BO-SO)}$ bits in the SD Bitmap field shall be set to zero.

The Channel Hopping Specification field is present only if the value of Channel Diversity Mode field in DSME Superframe Specification is set to indicate channel hopping. The Channel Hopping Specification field shall be formatted as illustrated in Figure 10-40.

Octets: 1	1	2	1	variable
Hopping Sequence ID	PAN Coordinator BSN	Channel Offset	Channel Offset Bitmap Length	Channel Offset Bitmap

Figure 10-40—Format of the Channel Hopping Specification field

The Hopping Sequence ID field contains the ID of the channel hopping sequence in use. The Hopping Sequence ID field set to zero indicates that a default hopping sequence shall be used. A Hopping Sequence ID field set to one indicates that a hopping sequence generated by the PAN coordinator shall be used. The other values of Hopping Sequence ID denote that the sequence is set by a higher layer. If the Hopping Sequence ID is one, a device shall request a channel hopping sequence from its coordinator when it associates to a PAN.

The PAN Coordinator BSN field shall contain the BSN of the PAN coordinator.

The Channel Offset field shall contain the channel hopping offset value of the device.

The Channel Offset Bitmap Length field shall be set to the length of the Channel Offset Bitmap field in octets.

The Channel Offset Bitmap field shall indicate the occupancy of the channel hopping offset values among neighbor devices and be represented in that bitmap. Each bit shall be set to one if the corresponding channel hopping offset value is already occupied by the neighbor devices. Otherwise, it shall be set to zero if the

corresponding channel hopping value is not occupied. For instance, a Channel Offset Bitmap of 0b1100100..0 indicates that channel hopping offset values of 0, 1, and 4 are being used by neighbor devices.

NOTE—The $(i)^{\text{th}}$ bit in the Channel Offset Bitmap corresponds to $(i-1)^{\text{th}}$ channel offset value.

10.4.11.2 Extended DSME PAN Descriptor IE

The format of the Extended DSME PAN Descriptor IE Content field shall be as illustrated in Figure 10-41.

Octets: 2	variable	2	8	variable	variable	0/1	variable
Superframe Specification	Pending Address	Extended DSME Superframe Specification	Time Synchronization Specification	Beacon Bitmap	Channel Hopping Specification	Hopping Sequence Length	Hopping Sequence

Figure 10-41—Extended DSME PAN Descriptor IE Content field format

The Superframe Specification field is described in 7.3.1.4.

The Pending Address field is described in 7.3.1.6.

The Extended DSME Superframe Specification field shall be formatted as illustrated in Figure 10-42.

Bits: 0–7	8	9	10	11	12	13–15
Multi-superframe Order	Channel Diversity Mode	Reserved	CAP Reduction	Deferred Beacon	Hopping Sequence Present	Reserved

Figure 10-42—Format of the Extended DSME Superframe Specification field

The Multi-superframe Order field is defined in 10.4.11.1.

The Channel Diversity Mode field is defined in 10.4.11.1.

The CAP Reduction field is defined in 10.4.11.1.

The Deferred Beacon field is defined in 10.4.11.1.

The Hopping Sequence Present field shall be set to one if an Association Request command is received before the Enhanced Beacon frame transmission and the Hopping Sequence ID of one is used in the DSME-enabled PAN.

The Time Synchronization Specification field is described in 10.4.11.1.

The Beacon Bitmap field is described in 10.4.11.1.

The Channel Hopping Specification field is described in 10.4.11.1 and is present only if the Channel Diversity Mode field in the Extended DSME Superframe Specification is set to indicate channel hopping.

The Hopping Sequence Length field is described in 10.4.11.1 and is present only if the Hopping Sequence Present field of the Extended DSME Superframe Specification field is one.

The Hopping Sequence field is described in 10.4.11.1 and is present only if the Hopping Sequence Present field of the Extended DSME Superframe Specification field is one.

10.4.12 MAC commands for DSME

10.4.12.1 DSME Association Request command

This command may be sent by an unassociated device that wishes to associate with a PAN. A device shall only associate with a PAN through the PAN coordinator or a coordinator allowing association, as determined through the scan procedure.

The Source Addressing Mode field of the Frame Control field shall be set to indicate extended addressing. The Destination Addressing Mode field shall be set to the same mode as indicated in the Beacon frame to which the DSME Association Request command refers.

The Frame Pending field of the Frame Control field shall be set to zero and ignored upon reception, and the AR field shall be set to one.

The Destination PAN ID field shall contain the identifier of the PAN to which to associate. The Destination Address field shall contain the address from the Beacon frame that was transmitted by the coordinator to which the DSME Association Request command is being sent. The Source PAN ID field shall contain the broadcast PAN ID. The Source Address field shall contain the value of *macExtendedAddress*. The PAN ID Compression field shall be set as specified in 7.2.2.6.

The DSME Association Request command Content field shall be formatted as illustrated in Figure 10-43.

Octets: 1	1	2	0/1
Capability Information	Hopping Sequence ID	Channel Offset	Extended DSME GTS Allocation

Figure 10-43—DSME Association Request command Content field format

The Capability Information field shall be formatted as illustrated in Figure 10-44.

Bits: 0	1	2	3	4	5	6	7
Reserved	Device Type	Power Source	Receiver On When Idle	DSME Association Type	Suspendable CSMA-CA	Security Capability	Allocate Address

Figure 10-44—Capability Information field format

The Device Type field, Power Source field, Receiver On When Idle field, Suspendable CSMA-CA field, Security Capability field, and Allocate Address field are described in 10.21.5.1.

The DSME Association Type field shall be set to one if a device requests assignment of a DSME GTS by a coordinator during association. Otherwise, the DSME Association Type field shall be set to zero.

The Hopping Sequence ID field shall indicate the ID of the channel hopping sequence in use. A Hopping Sequence ID of zero indicates that a default hopping sequence shall be used. A Hopping Sequence ID of one indicates that a hopping sequence generated by the PAN coordinator shall be used. Any other value of the Hopping Sequence ID denotes the sequence set by a higher layer shall be used. A device is requesting a channel hopping sequence from its coordinator if the Hopping Sequence ID is one.

The Channel Offset field shall be set to the offset value of the unassociated device that wishes to associate with a PAN. This value is specified by the next higher layer.

The Extended DSME GTS Allocation field shall be present if *macExtendedDsmeEnabled* is TRUE and the value of the DSME Association Type field is one. This field shall be formatted as illustrated in Figure 10-45.

Bits: 0	1–4	5–7
Direction	Allocation Order	Reserved

Figure 10-45—Extended DSME GTS Allocation field format

The Direction field specifies the direction of the DSME GTSs, which is relative to the data flow from the requesting device. The direction is specified as either transmit or receive. The value of this field shall be set to zero if the allocation is for transmission. The value shall be set to one if the allocation is for reception.

The Allocation Order field is described in 10.4.12.2.

10.4.12.2 DSME Association Response command

This command shall only be sent by an unassociated device that wishes to associate with a PAN. A device shall only associate with a PAN through the PAN coordinator or a coordinator allowing association, as determined through the scan procedure.

The Destination Addressing Mode and Source Addressing Mode fields of the Frame Control field shall each be set to indicate extended addressing.

The Frame Pending field of the Frame Control field shall be set to zero and ignored upon reception, and the AR field shall be set to one.

The Destination PAN ID field shall contain the value of *macPanId*, while the Source PAN ID field shall be omitted. The Destination Address field shall contain the extended address of the device requesting association. The Source Address field shall contain the value of *macExtendedAddress*. The PAN ID Compression field shall be set as specified in 7.2.2.6.

The DSME Association Response command Content field shall be formatted as illustrated in Figure 10-46.

Octets: 2	1	0/1	variable	0/1	0/1	0/2	0/1	0/2
Short Address	Association Status	Hopping Sequence Length	Hopping Sequence	Allocation Order	BI Index	Superframe ID	Slot ID	Channel Index

Figure 10-46—DSME Association Response command Content field format

If the coordinator was not able to associate this device to its PAN, the Short Address field shall be set to 0xffff, and the Association Status field shall contain the reason for the failure. If the coordinator was able to associate the device to its PAN, this field shall contain the short address that the device may use in its communications on the PAN until it is disassociated.

A Short Address field value equal to 0xffffe shall indicate that the device has been successfully associated with a PAN, but has not been allocated a short address. In this case, the device shall communicate on the PAN using only its 64-bit extended address.

The Association Status field shall contain one of the non-reserved values listed in Table 10-102.

The Hopping Sequence Length field shall specify the length of the Hopping Sequence used in the PAN if the PAN runs in both superframe structure mode and channel hopping mode. When the value of HoppingSequenceId is other than one or DsmeAssociation is one, this field shall be set to zero. The Hopping Sequence field shall be present only if the value of the Hopping Sequence Length field is not zero.

The Hopping Sequence field shall contain the current value of *macHoppingSequenceList*. The size of the Hopping Sequence field is defined by the Hopping Sequence Length field and the Hopping Sequence field contains the current value of *macHoppingSequenceList*. This field shall be present only if the PAN runs in both superframe structure mode and channel hopping mode and the value of the Hopping Sequence Length field is not zero.

The Allocation Order field shall be present if *macExtendedDsmeEnabled* is TRUE and the DsmeAssociation parameter of the device requesting association is set to one. This field shall indicate the DSME GTS allocation interval and be set to the value of AllocationOrder, *AO*, of the device requesting association. The value of *AO* and the DSME GTS allocation interval are related as follows:

$$\text{DSME-GTS allocation interval} = BI \times 2^{(MO-BO)} / 2^{AO} \text{ for } MO > BO$$

If $MO \leq BO$, the DSME GTS allocation interval is the same as an *MD*.

The BI Index field shall be present if *macExtendedDsmeEnabled* is TRUE and the DsmeAssociation parameter of the device requesting association is set to one. This field shall contain the index of the beacon interval *macBiIndex*, *BI*, in which the DSME GTS needs to be allocated. The BI Index is the sequence number of the *BI* in a multi-superframe beginning from zero.

A device can locate the value of BI Index in which the DSME Associate response command is received by using the value of *macPanCoordinatorBsn* as follows:

$$\text{BI Index} = \text{macPanCoordinatorBsn \% } 2^{(MO-BO)}$$

The Superframe ID field shall be present if *macExtendedDsmeEnabled* is TRUE and the DsmeAssociation parameter of the device requesting association is set to one. This field shall contain the index of the superframe in which the DSME GTS needs to be allocated. The Superframe ID is the sequence number of the superframe in a multi-superframe beginning from zero. The superframe in which the PAN coordinator sends its beacons serves as the reference point (Superframe ID 0). An example of superframe IDs is illustrated in Figure 10-25.

The Slot ID field shall be present if *macExtendedDsmeEnabled* is TRUE and the DsmeAssociation parameter of the device requesting association is set to one. This field shall contain the index of the DSME GTS to be allocated. The slot ID is the sequence number of the DSME GTS in a superframe beginning from zero. An example of slot IDs is illustrated in Figure 10-25.

The Channel Index field shall be present if *macExtendedDsmeEnabled* is TRUE and the DsmeAssociation parameter of the device requesting association is set to one. This field shall contain the channel number of the DSME GTS to be allocated.

10.4.12.3 DSME GTS Request command

Only devices that have been assigned a short address shall send this command in the CAP.

The Destination Addressing Mode and the Source Addressing Mode fields of the Frame Control field shall both be set to indicate short addressing.

The Frame Pending field of the Frame Control field shall be set to zero and ignored upon reception, and the AR field shall be set to one.

The Source PAN ID field shall contain the value of *macPanId*, and the Source Address field shall contain the value of *macShortAddress*.

The Destination PAN ID field shall contain the value of *macPanId*, and the Destination Address field shall be set to the short address of the destination device.

The DSME GTS Request command Content field shall be formatted as illustrated in Figure 10-47.

Octets: 1	0/1	0/2	0/1	variable	0/1
DSME GTS Management	Number of Slots	Preferred Superframe	Preferred Slot ID	DSME SAB Specification	Allocation Order

Figure 10-47—DSME GTS Request command Content field format

The DSME GTS Management field shall be formatted as illustrated in Figure 10-48.

Bits: 0–2	3	4	5–7
Management Type	Direction	Prioritized Channel Access	Reserved

Figure 10-48—DSME GTS Management field format

The Management Type field shall be set to one of the non-reserved values listed in Table 10-20.

Table 10-20—Values of the Management Type field

Management Type value (b2 b1 b0)	Description
000	Deallocation
001	Allocation
010	Duplicated allocation notification
011	Reduce
100	Restart
101	DSME GTS expiration
110–111	Reserved

The Direction field shall indicate the DSME GTSs are being allocated for TX or for RX of the requesting device. The value of this field is set to zero if the allocation is for TX. The value of this field is set to one if the allocation is for RX. This field is ignored if the management type is not allocation.

The Prioritized Channel Access field shall be set to one if the DSME GTS should be reserved as high priority, or set to zero if the DSME GTS should be reserved as low priority. When the DSME GTS request command is used in the DSME GTS change procedure, the Prioritized Channel Access shall be set according to the original DSME GTS.

The Number of Slots field shall contain the number of DSME GTSs that this command is requesting. This field is valid only if the management type is allocation.

The Preferred Superframe ID field shall contain the index of the preferred superframe in which the DSME GTSs need be allocated. The superframe ID is the sequence number of the superframe in a multi-superframe beginning from zero. The superframe in which the PAN coordinator sends its beacons serves as the reference point (Superframe ID 0). An example of superframe IDs is illustrated in Figure 10-25. This field is valid only if the management type is allocation.

The Preferred slot ID shall contain the index of the preferred slot from which the DSME GTSs need to be allocated. The slot ID is the sequence number of the DSME GTSs (not including beacon or CAP slots) in a superframe beginning from zero. An example of slot IDs is illustrated in Figure 10-25. This field is valid only if the management type is allocation.

The DSME SAB Specification field shall be formatted as illustrated in Figure 10-49.

Octets: 1	2	variable
DSME SAB Sub-block Length	DSME SAB Sub-block Index	DSME SAB Sub-block

Figure 10-49—DSME SAB Specification field format

The DSME SAB Sub-block Length field shall contain the length of the DSME SAB sub-block in units defined in Figure 10-27 for channel adaptation mode or in Figure 10-29 for channel hopping mode.

The DSME SAB Sub-block Index field shall indicate the beginning of the DSME SAB sub-block in the entire SAB as illustrated in Figure 10-27 for channel adaptation mode or in Figure 10-29 for channel hopping mode.

The DSME SAB sub-block shall contain the sub-block of the DSME Slot Allocation Bitmap as described in Figure 10-27 for channel adaptation mode or in Figure 10-29 for channel hopping mode. However, the meaning of zeros and ones in the DSME SAB sub-block has different meaning from the descriptions in those figures if the management type is not allocation. If the management type is allocation, the ones in the DSME SAB Sub-block field indicate already allocated or unavailable slots and the zeros indicate vacant and available slots. If the management type is not allocation, the ones in the DSME SAB Sub-block field indicate the slots that are being requested for deallocation, duplicated allocation notification, reduce, or restart.

The Allocation Order field shall be present if *macExtendedDsmeEnabled* is TRUE. This field shall indicate the DSME GTS allocation interval and be set to the value of AllocationOrder of the device requesting a DSME GTS. The relationship between the value of this field and the DSME GTS allocation interval is described in 10.4.12.2.

10.4.12.4 DSME GTS Response command

Only devices that have been assigned a short address shall send this command in the CAP.

The Destination Addressing Mode and the Source Addressing Mode fields of the Frame Control field shall both be set to indicate short addressing.

The Frame Pending field of the Frame Control field shall be set to zero and ignored upon reception, and the AR field shall be set to one.

The Source PAN ID field shall contain the value of *macPanId*, and the Source Address field shall contain the value of *macShortAddress*.

The Destination PAN ID field shall contain the value of *macPanId*, and the Destination Address field shall be set to the broadcast PAN ID.

The DSME GTS Response command Content field shall be formatted as illustrated in Figure 10-50.

Octets: 1	2	0/2	variable	0/1	0/1	0/2	0/1	0/2
DSME GTS Management	Destination Address	Channel Offset	DSME SAB Specification	Allocation Order	BI Index	Superframe ID	Slot ID	Channel Index

Figure 10-50—DSME GTS Response command Content field format

The DSME GTS Management field shall be formatted as illustrated in Figure 10-51.

Bits: 0–2	3	4	5–7
Management Type	Direction	Prioritized Channel Access	Dsme Gts Status

Figure 10-51—DSME GTS Management field format

The Management Type field shall be set to one of the non-reserved values listed in Table 10-20.

The Direction field shall indicate the DSME GTSs are being allocated for TX or for RX of the requesting device. The value of this field is set to zero if the allocation is for TX. The value of this field is set to one if the allocation is for RX. This field is ignored if the management type is not allocation.

The Prioritized Channel Access field shall be set to one if DSME GTS should be reserved as high priority, or set to zero if DSME GTS should be reserved as low priority. When the DSME GTS request command is used in the DSME GTS change procedure, the Prioritized Channel Access shall be set according to the original DSME GTS.

The Dsme Gts Status field indicates the result of a request. Valid values of the Dsme Gts Status field are given in Table 10-21.

The DSME GTS Destination Address field shall contain the short address of the destination device.

The Channel Offset field shall contain the channel offset of the RX device of the allocated DSME GTSs. This field is not valid in the channel adaptation mode.

Table 10-21—Dsme Gts Status field values

Status (b0 b1 b2)	Description
000	Approved
001	Disapproved: lack of availability
010	Disapproved: unknown GTS
011–111	Reserved

The DSME SAB Specification field is defined in 10.4.12.3.

The Allocation Order field shall be present if *macExtendedDsmeEnabled* is TRUE. This field shall indicate the DSME GTS allocation interval and be set to the value of AllocationOrder of the device requesting a DSME GTS. The relationship between the value of this field and the DSME GTS allocation interval is described in 10.4.12.2.

The BI Index field shall be present if *macExtendedDsmeEnabled* is TRUE. This field shall contain the index of the beacon interval *macBiIndex*, *BI*, in which the DSME GTS needs to be allocated. The BI Index is the sequence number of the *BI* in a multi-superframe beginning from zero.

The Superframe ID field shall be present if *macExtendedDsmeEnabled* is TRUE. This field shall contain the index of the superframe in which the DSME GTS is to be allocated. The Superframe ID is the sequence number of the superframe in a multi-superframe beginning from zero. The superframe in which the PAN coordinator sends its beacons serves as the reference point (Superframe ID 0).

The Slot ID field shall be present if *macExtendedDsmeEnabled* is TRUE. This field shall contain the index of the DSME GTS to be allocated. The Slot ID is the sequence number of the DSME GTS in a superframe beginning from zero.

The Channel Index field shall be present if *macExtendedDsmeEnabled* is TRUE. This field shall contain the channel number of the DSME GTS to be allocated.

10.4.12.5 DSME GTS Notify command

Only devices that have been assigned a short address shall send this command in the CAP.

The Destination Addressing Mode and the Source Addressing Mode fields of the Frame Control field shall both be set to indicate short addressing.

The Frame Pending field of the Frame Control field shall be set to zero and ignored upon reception, and the AR field shall be set to one.

The Source PAN ID field shall contain the value of *macPanId*, and the Source Address field shall contain the value of *macShortAddress*.

The Destination PAN ID field shall contain the value of *macPanId*, and the Destination Address field shall be set to broadcast PAN ID.

The DSME GTS Notify command Content field shall be formatted as illustrated in Figure 10-52.

Octets: 1	2	0/2	variable
DSME GTS Management	Destination Address	Channel Offset	DSME SAB Specification

Figure 10-52—DSME GTS Notify command Content field format

The DSME GTS Management field shall be formatted as illustrated in Figure 10-51.

The Management Type field shall be set to one of the non-reserved values listed in Table 10-20.

The Direction field shall indicate the DSME GTSs are being allocated for TX or for RX of the requesting device. The value of this field is set to zero if the allocation is for TX. The value of this field is set to one if the allocation is for RX. This field is ignored if the management type is not allocation.

The Prioritized Channel Access field shall be set to one if DSME GTS should be reserved as high priority, or set to zero if DSME GTS should be reserved as low priority. When the DSME GTS request command is used in the DSME GTS change procedure, the Prioritized Channel Access shall be set according to the original DSME GTS.

The Dsme Gts Status field indicates the result of a DSME GTS request. Valid values of the Dsme Gts Status field are given in Table 10-21.

The DSME GTS Destination Address shall contain the short address of the Destination device.

The Channel Offset field shall contain the channel offset of the RX device of the allocated DSME GTSs. This field is not valid in the channel adaptation mode.

The DSME SAB Specification field is defined in 10.4.12.3.

10.4.12.6 DSME Information Request command

The DSME Information Request command Content field shall be formatted as illustrated in Figure 10-53.

Octets: 1	1	2
Info Type	DSME SAB Sub-block Length	DSME SAB Sub-block Index

Figure 10-53—DSME Information Request command Content field format

The Info Type field indicates the type of DSME information that is requested by the device. Valid values of the Info Type field are given in Table 10-22.

The DSME SAB Sub-block Length field shall contain the length of the DSME SAB sub-block in units defined in Figure 10-27 for channel adaptation mode or in Figure 10-29 for channel hopping mode. This field is valid only if the value of the Info Type field is set to request the DSME SAB specification.

The DSME SAB Sub-block Index field shall indicate the beginning of the DSME SAB sub-block in the entire SAB as illustrated in Figure 10-27 for channel adaptation mode or in Figure 10-29 for channel hopping mode. This field is valid only if the value of the Info Type field is set to request the DSME SAB specification.

Table 10-22—Info Type field values

Info Type value	Information requested
0	Timestamp
1	DSME SAB Specification
2	DSME PAN descriptor
3–255	Reserved

10.4.12.7 DSME Information Response command

The DSME Information Response command Content field shall be formatted as illustrated in Figure 10-54.

Octets: 1	6	2	1	variable	variable
Info Type	Timestamp	Superframe ID	Slot ID	DSME SAB Specification	DSME PAN Descriptor

Figure 10-54—DSME Information Response command Content field format

The Info Type field indicates the type of DSME information that was requested. Valid values for the Info Type field are given in Table 10-23.

Table 10-23—Info Type field

Info Type value	Fields present
0	Timestamp, Superframe ID, Slot ID
1	DSME SAB Specification
2	DSME PAN Descriptor
3–255	Reserved

The Timestamp field shall contain the time, in symbols, at which this command was transmitted. The time is measured from the first symbol of the most recent beacon transmitted by the coordinator.

The Superframe ID field shall contain the ID of the superframe in which this command will be transmitted. The superframe ID is the sequence number of the superframe in a multi-superframe beginning from zero.

The Slot ID field shall contain the ID of the superframe slot in which this command will be transmitted. The slot ID is the sequence number of the DSME GTSs (not including beacon or CAP slots) in a superframe beginning from zero. This field is valid only if the value of the Info Type field is zero.

The DSME SAB Specification field shall be formatted as illustrated in Figure 10-49.

The DSME SAB Sub-block Length field shall contain the length of the DSME SAB sub-block in units defined in Figure 10-29.

The DSME SAB Sub-block Index field shall indicate the beginning of the DSME SAB Sub-block in the entire SAB as illustrated in Figure 10-29.

The DSME SAB Sub-block field shall contain the sub-block of the DSME Slot Allocation Bitmap as illustrated in Figure 10-29.

The DSME PAN Descriptor field shall be set as described in 10.4.11.1.

10.4.12.8 DSME Beacon Allocation Notification command

The Destination Addressing Mode and Source Addressing Mode fields of the Frame Control field shall both be set to indicate short addressing.

The Frame Pending field of the Frame Control field shall be set to zero and ignored upon reception, and the AR field shall be set to zero.

The Destination PAN ID field shall contain the value of *macPanId*, while the Source PAN ID field shall be omitted. The Destination Address field shall be set to 0xffff. The Source Address field shall contain the value of *macShortAddress*. The PAN ID Compression field shall be set as specified in 7.2.2.6.

The DSME Beacon Allocation Notification command Content field shall be formatted as illustrated in Figure 10-55.

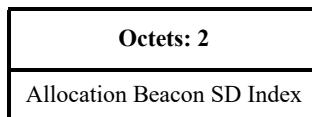


Figure 10-55—DSME Beacon Allocation Notification command Content field format

The Allocation Beacon SD Index field shall contain the allocating SD index number for the Beacon frame that is allocated to the Source device.

10.4.12.9 DSME Beacon Collision Notification command

The Destination Addressing Mode and Source Addressing Mode fields of the Frame Control field shall both be set to indicate short addressing.

The Frame Pending field of the Frame Control field shall be set to zero and ignored upon reception, and the AR field shall be set to one.

The Destination PAN ID field shall contain the value of *macPanId*, while the Source PAN ID field shall be omitted. The Destination Address field shall be set to the node address that has requested later. The Source Address field shall contain the value of *macShortAddress*. The PAN ID Compression field shall be set as specified in 7.2.2.6.

The DSME Beacon Collision Notification command Content field shall be formatted as illustrated in Figure 10-56.

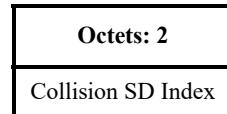


Figure 10-56—DSME Beacon Collision Notification command Content field format

The Collision SD Index field shall contain the SD index number of the collision Beacon frame.

10.4.12.10 DSME Link Report command

The Source Addressing Mode field of the Frame Control field shall be set to indicate extended addressing, and the Destination Addressing Mode field shall be set to the same mode as the destination device to which the command is sent.

The Frame Pending field of the Frame Control field shall be set to one, and the AR field shall be set to one.

The Destination PAN ID field shall contain the identifier of the PAN of the destination device. The Destination Address field shall contain the address of the destination device.

The Source PAN ID field shall contain the value of *macPanId*, and the Source Address field shall contain the value of *macShortAddress*.

The DSME Link Report command Content field shall be formatted as illustrated in Figure 10-57.

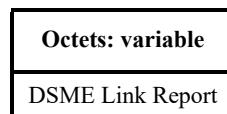


Figure 10-57—DSME Link Report command Content field format

The DSME Link Report field shall be formatted as illustrated in Figure 10-58.

Octets: 1	4	...	4
Link Descriptor Count	Link Descriptor 1	...	Link Descriptor <i>n</i>

Figure 10-58—DSME Link Report field format

The Link Descriptor Count field specifies the number of the Link Descriptors in the DSME Link Report field.

The Link Descriptor shall be formatted as illustrated in Figure 10-59.

Octets: 1	1	1	1
Channel	Average LQI	Average RSSI	Reserved

Figure 10-59—Link Descriptor field format

The Channel field specifies the channel index reported by the source device.

The Average LQI field contains the average received LQI of the channel specified in Channel field within *macLinkStatisticPeriod* symbols.

The Average receive signal strength indicator (RSSI) field contains the average received signal power by ED measurement during a period of *macLinkStatisticPeriod* symbols. The Average RSSI measurement shall be performed for each received packet, and the use of the Average RSSI result by the next higher layer is not specified in this standard.

10.4.13 MAC management service primitives for DSME

10.4.13.1 General

In a DSME-enabled PAN, the primitives listed in Table 10-24 shall be implemented.

Table 10-24—DSME MLME-SAP primitives

Name	Request	Indication	Response	Confirm
MLME-DSME-GTS	10.4.13.2.2	10.4.13.2.3	10.4.13.2.4	10.4.13.2.5
MLME-DSME-LINK-REPORT	10.4.13.3.1	10.4.13.3.2	—	10.4.13.3.3

10.4.13.2 Primitives for DSME GTS management

10.4.13.2.1 General

The MLME-SAP DSME GTS management primitives define how DSME GTSs are requested and maintained. A device wishing to use these primitives and DSME GTSs in general will already be tracking the beacons of its coordinator.

10.4.13.2.2 MLME-DSME-GTS.request

This primitive allows a DSME-enabled device to perform one of the following actions:

- Allocation of a new DSME GTS
- Deallocation of an existing DSME GTS
- Notification of a duplicated allocation
- Reduction of existing DSME GTSs
- Restart of existing DSME GTSs

The semantics of this primitive are as follows:

```
MLME-DSME-GTS.request      (
    DeviceAddress,
    ManagementType,
    Direction,
    PrioritizedChannelAccess,
    NumSlot,
    PreferredSuperframeId,
    PreferredSlotId,
    DsmeSabSpecification,
    SecurityParams,
    AllocationOrder
)
```

The primitive parameters are defined in Table 10-25.

Table 10-25—MLME-DSME-GTS.request parameters

Name	Type	Valid range	Description
DeviceAddress	Integer	0x0000–0xffffd	The address of the neighboring device to request the management of DSME GTSs.
ManagementType	Enumeration	DEALLOCATION, ALLOCATION, DUPLICATE_ALLOCATION, REDUCE, RESTART, EXPIRATION	The type of the management request.
Direction	Enumeration	TX, RX	The direction of DSME GTSs.
PrioritizedChannelAccess	Enumeration	LOW, HIGH	The priority level.
NumSlot	Integer	0x00–0xff	The number of slots to be requested for allocation. This parameter is ignored if the ManagementType is not ALLOCATION.
PreferredSuperframeId	Integer	0x0000–0xffff	The index of the preferred superframe in a multi-superframe. This parameter is ignored if the ManagementType is not ALLOCATION.
PreferredSlotId	Integer	0x00–0x0e	The index of the preferred slot in the preferred superframe. This parameter is ignored if the ManagementType is not ALLOCATION.
DsmeSabSpecification	—	As defined in Table 10-26	If the ManagementType is ALLOCATION, this parameter contains the information of the current DSME GTS allocation and slot availability in one hop neighborhood of the requesting device. If the ManagementType is not 0b001, this parameter indicates the DSME GTSs to deallocate, notify duplicated allocation, reduce, or restart.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.
AllocationOrder	Integer	0x00–0x08	As defined in 10.4.12.2.

The elements of the DsmeSabSpecification are given in Table 10-26.

Table 10-26—Elements of a DsmeSabSpecification

Name	Type	Valid range	Description
DsmeSabSubBlockLength	Integer	0x00–0xff	The length of the DSME SAB sub-block in units in Figure 10-27 for channel adaptation mode or in Figure 10-29 for channel hopping mode.
DsmeSabSubBlockIndex	Integer	0x0000–0xffff	The beginning of the DSME SAB sub-block in the entire SAB as illustrated in Figure 10-27 for channel adaptation mode or in Figure 10-29 for channel hopping mode.
DsmeSabSubBlock	Integer	—	The sub-block of the DSME SAB as described in Figure 10-27 for channel adaptation mode or in Figure 10-29 for channel hopping mode.

The MLME-DSME-GTS.request primitive is generated by the higher layer of a device and issued to its MLME to request the allocation of new DSME GTSS or to request the deallocation, duplicated allocation notification, reduce, or change of existing DSME GTSS.

On receipt of the MLME-DSME-GTS.request primitive, the MLME of the device shall send a DSME GTS Request command, as described in 10.4.12.3, to the DeviceAddress. The ManagementType, Direction, PrioritizedChannelAccess, NumSlot, PreferredSuperframeId, PreferredSlotId, DsmeSabSubBlockIndex, and DsmeSabSubBlockLength parameters shall be contained in the corresponding fields of the command. The DSME SAB Sub-block field shall contain a bitmap of a sub-block of *macDsmeSab*. The DsmeSabSubBlockIndex and DsmeSabSubBlockLength indicate the bitmap of which sub-block shall be contained in the command.

If *macShortAddress* is equal to 0xffffe or 0xffff, the Source device is not permitted to request a DSME GTS allocation. In this case, the MLME issues the MLME-DSME-GTS.confirm primitive containing a Status of NO_SHORT_ADDRESS.

If the DSME GTS Request command cannot be sent due to the channel condition, the MLME shall issue the MLME-DSME-GTS.confirm primitive with a Status of CHANNEL_ACCESS_FAILURE.

If the MLME successfully transmits a DSME GTS request command, the MLME expects an acknowledgment in return. If an acknowledgment is not received, the MLME shall issue the MLME-DSME-GTS.confirm primitive with a Status of NO_ACK.

If the DSME GTS Response command from the destination device is not received within the expected time, the MLME of the source device shall notify the next higher layer of the failure by the MLME-DSME-GTS.confirm primitive with a Status of NO_DATA.

10.4.13.2.3 MLME-DSME-GTS.indication

This primitive reports the reception of a DSME GTS request command.

The semantics of this primitive are as follows:

```
MLME-DSME-GTS.indication ( 
    DeviceAddress,
    ManagementType,
    Direction,
    PrioritizedChannelAccess,
    NumSlot,
    PreferredSuperframeId,
    PreferredSlotId,
    DsmeSabSpecification,
    AllocationOrder
)
```

The primitive parameters are defined in Table 10-27.

Table 10-27—MLME-DSME-GTS.indication parameters

Name	Type	Valid range	Description
DeviceAddress	Short address	0x0000–0xffff	The address of the device that has transmitted the received DSME GTS request command.
ManagementType	Enumeration	DEALLOCATION, ALLOCATION, DUPLICATED_ALLOCATION, REDUCE, RESTART, EXPIRATION	The type of the management request.
Direction	Enumeration	TX, RX	The direction of DSME GTSs.
PrioritizedChannelAccess	Enumeration	LOW, HIGH	The priority level.
NumSlot	Integer	0x00–0xff	The number of slots to be requested for allocation. This parameter is ignored if the ManagementType is not ALLOCATION.
PreferredSuperframeId	Integer	0x0000–0xffff	The index of the preferred superframe in a multi-superframe. This parameter is ignored if the ManagementType is not ALLOCATION.
PreferredSlotId	Integer	0x00–0x0e	The index of the preferred slot in the preferred superframe. This parameter is ignored if the ManagementType is not ALLOCATION.
DsmeSabSpecification	—	As defined in Table 10-26	If the ManagementType is ALLOCATION, this parameter contains the information of the current DSME GTS allocation and slot availability in one hop neighborhood of the requesting device. If the ManagementType is not ALLOCATION, this parameter indicates the DSME GTSs to deallocate, notify duplicated allocation, reduce, or restart.
AllocationOrder	Integer	0x00–0x08	As defined in 10.4.12.1.

This primitive is generated by the MLME of a device and issued to its next higher layer upon the reception of a DSME GTS Request command.

On receipt of the MLME-DSME-GTS.indication primitive, the higher layer is notified of the reception of a DSME GTS request.

10.4.13.2.4 MLME-DSME-GTS.response

This primitive allows the next higher layer of a device to respond to the MLME-DSME-GTS.indication primitive.

The semantics of this primitive are as follows:

```
MLME-DSME-GTS.response ( 
    DeviceAddress,
    ManagementType,
    Direction,
    PrioritizedChannelAccess,
    ChannelOffset,
    DsmeSabSpecification,
    AllocationOrder,
    BiIndex,
    SuperframeId,
    SlotId,
    ChannelIndex,
    DsmeGtsStatus
)
```

The primitive parameters are defined in Table 10-28.

Table 10-28—MLME-DSME-GTS.response parameters

Name	Type	Valid range	Description
DeviceAddress	Short address	0x0000–0xffffd	The address of the device that has transmitted the received DSME GTS request command.
ManagementType	Enumeration	DEALLOCATION, ALLOCATION, DUPLICATED_ ALLOCATION, REDUCE, RESTART, EXPIRATION	The type of the management request.
Direction	Enumeration	TX, RX	The direction of DSME GTSs.
PrioritizedChann elAccess	Enumeration	LOW, HIGH	The priority level.
ChannelOffset	Integer	0x0000–0xfffff	This parameter specifies the offset value of Hopping Sequence.
DsmeSabSpecific ation	—	As defined in Table 10-26	This parameter indicates the DSME GTSs to allocate, deallocate, notify duplicated allocation, reduce, or restart.
AllocationOrder	Integer	0x00–0x08	As defined in 10.4.12.1.
BiIndex	Integer	0x00–0xff	As defined in 10.4.12.1.
SuperframeId	Integer	0x0000–0xfffff	As defined in 10.4.12.1.

Table 10-28—MLME-DSME-GTS.response parameters (continued)

Name	Type	Valid range	Description
SlotId	Integer	0x00–0x0e	As defined in 10.4.12.1.
ChannelIndex	Integer	0x0000–0xffff	As defined in 10.4.12.1.
DsmeGtsStatus	Enumeration	As specified in Table 10-21	The status of the DSME-GTS request.

The MLME-DSME-GTS.response primitive can be generated by the next higher layer and issued to its MLME to respond to the allocation, deallocation, duplicated allocation notification, reduce, or restart of DSME GTS.

On receipt of the MLME-DSME-GTS.response primitive, the MLME of the device shall generate a DSME GTS Response command, as described in 10.4.12.4. The ManagementType, Direction, PrioritizedChannelAccess, ChannelOffset, and DsmeSabSpecification parameters shall be contained in the corresponding fields of the command. The DSME GTS Destination Address field shall be set to the value of DeviceAddress parameter. The Dsme Gts Status field of the command shall be set to the value DsmeGtsStatus parameter. Then the device shall send the DSME GTS Response command to its one-hop neighbors with the destination address set to the short broadcast address.

10.4.13.2.5 MLME-DSME-GTS.confirm

This primitive reports the results of a request to allocate, deallocate, notify duplicated allocation, reduce, or restart DSME GTSs to the higher layer of the device.

The semantics of this primitive are as follows:

```
MLME-DSME-GTS.confirm ( 
    DeviceAddress,
    ManagementType,
    Direction,
    PrioritizedChannelAccess,
    ChannelOffset,
    DsmeSabSpecification,
    DsmeGtsStatus,
    AllocationOrder,
    BilIndex,
    SuperframeId,
    SlotId,
    ChannelIndex,
    Status
)
```

The primitive parameters are defined in Table 10-29.

Table 10-29—MLME-DSME-GTS.confirm parameters

Name	Type	Valid range	Description
DeviceAddress	Short address	0x0000–0xffff	The address of the device that has transmitted the received DSME-GTS Response command.
ManagementType	Enumeration	DEALLOCATION, ALLOCATION, DUPLICATED_ALLOCATION, REDUCE, RESTART, EXPIRATION	The type of the management request.
Direction	Enumeration	TX, RX	The direction of DSME GTSSs.
PrioritizedChannelAccess	Enumeration	LOW, HIGH	The priority level.
ChannelOffset	Integer	0x0000–0xffff	This parameter specifies the offset value of Hopping Sequence.
DsmeSabSpecification	—	As defined in Table 10-26	This parameter indicates the DSME GTSSs to allocate, deallocate, notify duplicated allocation, reduce, or restart.
DsmeGtsStatus	Integer	As specified in Table 10-21	The Dsme Gts Status field of DSME GTS Response command.
AllocationOrder	Integer	0x00–0x08	As defined in 10.4.12.1.
BiIndex	Integer	0x00–0xff	As defined in 10.4.12.1.
SuperframeId	Integer	0x0000–0xffff	As defined in 10.4.12.1.
SlotId	Integer	0x00–0x0e	As defined in 10.4.12.1.
ChannelIndex	Integer	0x00–0x1f	As defined in 10.4.12.1.
Status	Enumeration	SUCCESS, NO_DATA, also see 8.2.2	The status of the request.

On receipt of a DSME GTS Response command, the device shall check the DSME GTS Destination Address field of the command.

If the DSME GTS Destination Address in this command is the same as *macShortAddress*, the device shall check the Status and DsmeGtsStatus parameters. If the value of the Status parameter is SUCCESS and the DsmeGtsStatus parameter is zero (APPROVED), the device shall generate a DSME GTS Notify command, as described in 10.4.6.2. The ManagementType, Direction, PrioritizedChannelAccess, ChannelOffset, and DsmeSabSpecification parameters shall be contained in the corresponding fields of the command. The DSME GTS Destination Address field shall be set to the value of DeviceAddress parameter. The DsmeGtsStatus parameter shall be set to have value of the Dsme Gts Status field of the command. Then the device shall broadcast the DSME GTS Notify command to its one-hop neighbor.

Also, the MLME of the device shall notify the higher layer with the result of the request to allocate, deallocate, notify duplicated allocation, reduce, or restart DSME GTSSs.

If the DSME GTS Destination Address field is different from *macShortAddress*, the device shall update its DSME SAB according to the DSME GTS SAB Specification of the received command.

On receipt of the MLME-DSME-GTS.confirm primitive, the higher layer is notified of the result of its request to notify duplicated allocation, reduce, or restart a DSME GTS.

10.4.13.3 Primitives for reporting the link status

10.4.13.3.1 MLME-DSME-LINK-REPORT.request

The MLME-DSME-LINK-REPORT.request primitive is used to request that a device start monitoring link quality statistic and periodically report the statistic results to the destination device.

The semantics of this primitive are as follows:

```
MLME-DSME-LINK-REPORT.request(
    DstAddr,
    ReportPeriod
)
```

The primitive parameters are defined in Table 10-30.

Table 10-30—MLME-DSME-LINK-REPORT.request parameters

Name	Type	Valid range	Description
DstAddr	Integer	0x0000–0xffff	Short address of the Destination device to which the DSME-link report request is intended.
ReportPeriod	Integer	0x000000–0xffffffff	The time interval between two DSME Link Status Report commands is defined as ReportPeriod × $aBaseSuperframeDuration \times 2^{MO}$ symbols. If the parameter equals to 0x000000, DSME Link Status Report command is not allowed to be sent.

On receipt of an MLME-DSME-LINK-REPORT.request primitive by a device, the MLME of the device attempts to generate a DSME Link Status Report command as described in 10.4.12.10 with the information contained in this primitive, and if successful, sends it to the destination device according to the DstAddr parameter.

If the DSME Link Status Report command cannot be sent due to a CSMA-CA algorithm failure, the MLME shall issue the MLME-DSME-LINK-REPORT.confirm primitive with a Status of CHANNEL_ACCESS_FAILURE.

If the MLME successfully transmits a DSME Link Status Report command, the MLME expects an acknowledgment in return. If an acknowledgment is not received, the MLME shall issue the MLME-DSME-LINK-REPORT.confirm primitive with a Status of NO_ACK.

If the DSME Link Status Report command has been acknowledged, the device shall send another DSME Link Report command again in the interval defined in the parameter ReportPeriod.

10.4.13.3.2 MLME-DSME-LINK-REPORT.indication

The MLME-DSME-LINK-REPORT.indication primitive is generated by the MAC sublayer and issued to the next higher layer on receipt of a DSME Link Status Report command.

The semantics of this primitive are as follows:

```
MLME-DSME-LINK-REPORT.indication(
    DstAddr,
    LinkReportSpecification
)
```

Table 10-31 specifies the parameters for the MLME-DSME-LINK-REPORT.indication request primitive.

Table 10-31—MLME-DSME-LINK-REPORT.indication parameters

Name	Type	Valid range	Description
DstAddr	Integer	0x0000–0xffff	Short address of the Destination device to which the DSME link report request is intended.
LinkReportSpecification	Link Report Specification	As defined in 10.4.12.10	As defined in 10.4.12.10.

The usage of the MLME-DSME-LINK-REPORT.indication primitive by the next higher layer is beyond the scope of this document.

10.4.13.3.3 MLME-DSME-LINK-REPORT.confirm

The MLME-DSME-LINK-REPORT.confirm primitive is generated by the MLME and issued to its next higher layer in response to an MLME-DSME-LINK-REPORT.request primitive.

The semantics of this primitive are as follows:

```
MLME-DSME-LINK-REPORT.confirm (
    Status
)
```

Table 10-32 specifies the parameters for the MLME-DSME-LINK-REPORT.confirm primitive.

Table 10-32—MLME-DSME-LINK-REPORT.confirm parameters

Name	Type	Valid range	Description
Status	Enumeration	SUCCESS, also see 8.2.2	The status of starting DSME link report.

The MLME-DSME-LINK-REPORT.confirm primitive returns a Status of either SUCCESS, indicating the MAC sublayer has started reporting its statistic results periodically, or the appropriate error code.

On receipt of the MLME-DSME-LINK-REPORT.confirm primitive by a device, the next higher layer is notified of the result of its request to start reporting link status in the PAN. If the request was successful, the Status parameter shall be set to SUCCESS. Otherwise, the Status parameter shall indicate the error.

10.4.14 MAC constants and PIB attributes for DSME

10.4.14.1 DSME specific MAC PIB attributes

DSME specific attributes are described in Table 10-33 and Table 10-34.

Table 10-33—DSME-specific MAC PIB attributes

Attribute	Type	Range	Description	Default
<i>macAllocationOrder</i>	Integer	0–8	As defined in 10.4.12.1. If $MO < BO$, the value shall be set to zero.	0
<i>macAvgLqi</i>	Integer	0x00–0xff	A characterization of the link quality between a source device and a destination device on the channel defined by Channel Index, the measurement shall be performed for each received packet during a period of <i>LinkStatusStatisticPeriod</i> .	—
<i>macAvgRssi</i>	Integer	0–255	Average RSSI.	—
<i>macBeaconSlotLength</i>	Integer	0x0000–0xffff	The number of symbols forming a beacon slot.	60
<i>macBiIndex</i>	Integer	0–255	As defined in 10.4.12.2.	0
<i>macCapReduction</i>	Boolean	TRUE, FALSE	Indication of whether the CAP reduction is enabled. A value of TRUE indicates that the CAP reduction is enabled.	FALSE
<i>macChannelDiversity-Mode</i>	Enumeration	ADAPTATION, HOPPING	Indicates the method of channel diversity in a PAN using superframe structure, either channel adaptation or channel hopping.	ADAPTATION
<i>macChannelIndex</i>	Integer	0–31	Specifies the channel index of the channel's DSME link reported by the source device.	—
<i>macDsmeChannelOffset</i>	Integer	0x0000–0xffff	ChannelOffset is the offset value of Hopping Sequence.	0
<i>macChannelOffsetBitmap</i>	Set of octets	—	A bitmap that represents whether the corresponding channel offset is used. If the corresponding channel offset is used, the bit value shall be set to one. Otherwise, it shall be set to zero. For instance, if the 1st, 2nd, 4th channels offset are used with ChannelOffsetBitmapLength of 16, ChannelOffsetBitmap shall be 0b0110100000000000.	—
<i>macChannelOffsetBitmapLength</i>	Integer	0x00–0xff	Specifies the length of <i>macChannelOffsetBitmap</i> in octets.	—
<i>macChannelStatus</i>	List of Link-Report entries as described in Table 10-31	Refer to Table 10-31	Link report for each used channel.	—

Table 10-33—DSME-specific MAC PIB attributes (continued)

Attribute	Type	Range	Description	Default
<i>macConnecDev</i>	Boolean	TRUE, FALSE	Indication of whether the device is a Connection Device or not. If this attribute is TRUE, the device is a Connection Device. This attribute shall be set to FALSE if the device is not a Connection Device.	FALSE
<i>macDeferredBeaconUsed</i>	Boolean	TRUE, FALSE	Indication of whether the device uses CCA before transmitting a beacon frame. A value of TRUE indicates that the device uses CCA before transmitting a beacon frame.	FALSE
<i>macDsmeAct</i>	List of Allocation Counter Tables, as defined in Table 10-35	—	A list of allocation counter tables of the DSME GTSs allocated to the device.	0
<i>macDsmeAssociation</i>	Boolean	TRUE, FALSE	Indicates whether DSME GTSs are allocated during the association procedure. This attribute is set to TRUE if a device requests assignment of a DSME GTS during association.	TRUE
<i>macDsmeGtsExpiration-Time</i>	Integer	0x00–0xff	The number of idle incidents before expiring a DSME GTS.	7
<i>macDsmeSab</i>	Bitmap	As defined in 10.4.12.7	The slot allocation bitmap of the DSME-GTS schedule.	0
<i>macLinkStatusStatisticPeriod</i>	Integer	0x000000–0xffffffff	The time interval between two times of link status statistics, which is defined as LinkStatusStatisticPeriod = $aBaseSuperframeDuration \times 2^M$ symbols. If the parameter equals to 0x000000, link status statistic is not allowed.	—
<i>macMultisuperframeOrder</i>	Integer	0–22	The length of a multi-superframe, which is a cycle of the repeated superframes.	15
<i>macNeighborInformationTable</i>	List of Neighbor Information entries as described in Table 10-34	—	A table of the neighbor device's information entries.	Null
<i>macPanCoordinatorBsn</i>	Integer	0x00–0xff	The sequence number added to the transmitted beacon frame of a PAN coordinator.	—
<i>macSdBitmap</i>	Bitmap	As defined in 10.4.11.1	Indicates the beacon frame allocation information of neighbor nodes. This field is expressed in bitmap format that orderly represents the schedule of beacons, with the corresponding bit set to one if a beacon is allocated in that SD.	—

Table 10-33—DSME-specific MAC PIB attributes (continued)

Attribute	Type	Range	Description	Default
<i>macSdIndex</i>	Integer	0x0000–0xffff	Specifies the allocating SD index number for beacon frame.	0x0000
<i>macSyncParentExtendedAddress</i>	IEEE address	—	The extended address of the coordinator through which the device is synchronized.	—
<i>macSyncParentSdIndex</i>	Integer	0x0000–0xffff	Indication of the SD index the synchronized parent used.	0
<i>macSyncParentShortAddress</i>	Integer	0x0000–0xffff	The short address assigned to the coordinator through which the device is synchronized. A value of 0xffffe indicates that the coordinator is only using its extended address. A value of 0xffff indicates that this value is unknown.	0xffff

Table 10-34—Elements of Neighbor Information

Attribute	Type	Range	Description
<i>ShortAddress</i>	Integer	0x0000–0xffff	The short address of the neighbor device.
<i>ExtendedAddress</i>	IEEE address	An extended address	The extended address of the neighbor device.
<i>SdIndex</i>	Integer	0x0000–0xffff	The allocating SD index number for beacon frame.
<i>ChannelOffset</i>	Integer	0x0000–0xffff	The offset value of ChannelHoppingSequence.
<i>TrackBeacon</i>	Boolean	TRUE, FALSE	TRUE if the MLME is to track all future beacons of the neighbor device. FALSE if the MLME is not to track beacons of the neighbor device.
<i>BeaconLostCount</i>	Integer	0x00–0xff	The number of consecutive lost beacons.
<i>AllocationOrder</i>	Integer	0–8	As defined in 10.4.12.1.
<i>AssociationType</i>	Integer	0–1	Indicates whether DSME GTSs are allocated during the association procedure. This element shall be set to one if DSME GTSs are allocated during association. Otherwise, it shall be set to zero.

The Allocation Counter Table format is defined in Table 10-35.

Table 10-35—Elements of Allocation Counter Table

Field	Type	Valid range	Description
Superframe ID	Integer	0x0000–0xffffd	The superframe ID of the DSME GTS in a multi-superframe.
Slot ID	Integer	0–14	The slot ID of the DSME GTS in the superframe.
Channel ID	Integer	0x0000–0xfffff	In channel adaptation, this field shall contain the Channel number of the DSME GTS. In channel hopping, this field shall contain the Channel Offset.

Table 10-35—Elements of Allocation Counter Table (continued)

Field	Type	Valid range	Description
Direction	Enumeration	TX, RX	The direction of the allocated DSME-GTS.
Prioritized Channel Access	Boolean	TRUE, FALSE	If set to TRUE, the DSME GTS is high priority, otherwise FALSE and the DSME GTS is low priority.
Source/Destination Address	Short address	0x0000–0xffffd	The short address of the device that is the source (if RX) or the destination of the allocated DSME-GTS.
Counter	Integer	0x0000–0xffff	An idle counter, in other words, the number of idle multi-superframes since the allocated DSME-GTS was used.
LinkQuality	Integer	0x0000–0xffff	The link quality of the allocated DSME-GTS.
Allocation Order	Integer	0x00–0x08	As defined in 10.4.12.1. If $MO \leq BO$, the value of <i>macAllocationOrder</i> shall be set to zero.
BI Index	Integer	0x00–0xff	As defined in 10.4.12.1.

10.5 Low energy (LE) using coordinated sampled listening (CSL)

10.5.1 Overview of LE and CSL

CSL allows receiving devices to periodically sample the channel(s) for incoming transmissions at low duty cycles. The receiving device and the transmitting device are coordinated to reduce transmitting overhead.

10.5.2 LE functional description

10.5.2.1 LE contention access period (LE CAP)

When *macCslPeriod* is nonzero, CSL is deployed in CAP. CSL behavior is defined in 10.5.4. The *macRitPeriod* shall be set to zero in a PAN using superframe structure.

When *macLowEnergySuperframeSupported* is TRUE, the transaction shall complete one IFS period before the end of the inactive period. If a device senses a frame in the CAP that does not end within the CAP when *macLowEnergySuperframeSupported* is TRUE, the device may continue receiving the frame until it ends before the end of the inactive period. When *macLowEnergySuperframeSupported* is TRUE, the coordinator shall not allocate GTSSs in order to avoid the interference from the frames exceeding the CAP and going into the CFP. When *macLowEnergySuperframeSupported* is TRUE, the coordinator shall notify the devices that already associated or intend to associate the condition of *macLowEnergySuperframeSupported* in the Beacon frames.

10.5.2.2 LE superframe structure

If *macLowEnergySuperframeSupported* is TRUE and *macLowEnergySuperframeSyncInterval* is not zero, the coordinator shall transmit Beacon frames not in every beacon interval, but once in every beacon interval time *macLowEnergySuperframeSyncInterval*, except when requested to do so. If *macLowEnergySuperframeSupported* is TRUE and *macLowEnergySuperframeSyncInterval* is zero, the coordinator shall transmit Beacon frames only when it is requested to do so.

10.5.2.3 LE-incoming and outgoing superframe timing

If a device supports *macLowEnergySuperframeSupported*, the beacon order and superframe order may be equal for all superframes on a PAN.

10.5.2.4 LE scan

When *macCslPeriod* is nonzero, CSL is deployed in channel scans. When *macCslMaxPeriod* is nonzero, each coordinator broadcasts Beacon frames with wake-up frame sequence. This allows devices to perform channel scans with low duty cycles.

10.5.3 LE transmission, reception, and acknowledgment with positive handshakes

When *macLeHsEnabled* is set to TRUE in the coordinator and the device, the data transmission, reception, and acknowledgment process illustrated in Figure 10-60 shall be used.

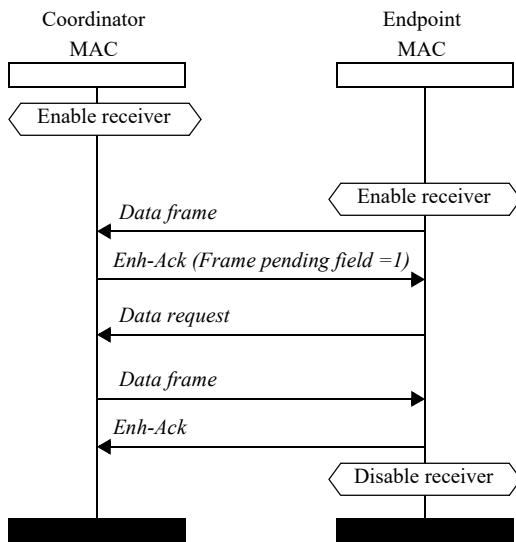


Figure 10-60—LE transmission with positive handshake

If the device received an Enh-Ack frame from the coordinator indicating that the coordinator has a pending frame, the device shall send a Data Request command to the coordinator and wait for the corresponding Data frame from the coordinator.

If the Enh-Ack frame is not received as expected, retransmission shall be performed as defined in 10.3.7.2. If, after sending the Enh-Ack frame with the Frame Pending field set, the Data Request command is not received, the coordinator waits for a retransmission and, if received, repeats the Enh-Ack frame with the Frame Pending field set.

10.5.4 Coordinated sampled listening (CSL)

10.5.4.1 General

The CSL mode is turned on when the PIB attribute *macCslPeriod* is nonzero and turned off when *macCslPeriod* is zero. In CSL mode, transmission, reception, and acknowledgment work as follows. Figure 10-61 illustrates the basic CSL operations.

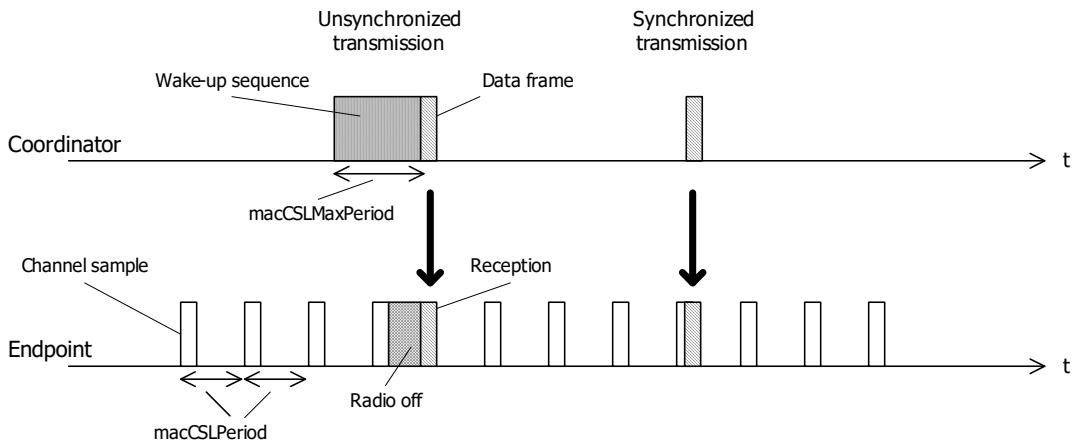


Figure 10-61—Basic CSL operations

A wake-up frame is a Multipurpose frame with the following:

- The AR field set to indicate no acknowledgment requested
- Only the Rendezvous Time IE, as defined in 10.5.5.2
- No payload

The CSL phase is the time from the first symbol of the MAC header containing the CSL IE, as defined in 10.5.5.1, was transmitted until the next time the device expects a possible future frame transmissions to the device to start, which is bounded by the next channel sample. For example, a synchronized transmission that does not include a wake-up sequence can transmit the first symbol of the frame at the time specified by the CSL phase and CSL period, in which case CCA has to be performed before.

10.5.4.2 CSL idle listening

During idle listening, the CSL coordinator performs a channel sample every *macCSlPeriod* time. If a wake-up frame is not received on the channel, the CSL coordinator disables the receiver until the next channel sample time and then performs the next channel sample. If the channel sample contains a wake-up frame, the CSL coordinator checks the destination address in the wake-up frame. Acknowledgment and retransmission are performed as described in 10.3.7.2, with the additional requirement that for each transmission, the process described in this subclause is used. If the destination address of the wake-up frame matches *macShortAddress*, the CSL coordinator checks whether the wake-up frame contains the Wake-up Interval field. If the wake-up frame does not contain the Wake-up Interval field, the CSL coordinator disables the receiver until the rendezvous time and then enables the receiver to receive the Data frame. If the wake-up frame does contain the Wake-up Interval field, and its value is nonzero, the CSL coordinator disables the receiver and transmits the data request frame with the AR field in the Data frame set to one. Then the CSL coordinator waits for the Enh-Ack frame. If the Enh-Ack frame is received, the rendezvous time is updated using the contents of the Enh-Ack frame, and the receiver remains on in order to receive the frame.

When the wake-up frame contains the Wake-up Interval field with a nonzero value, the transmission, reception, and acknowledgment operation is as illustrated in Figure 10-62.

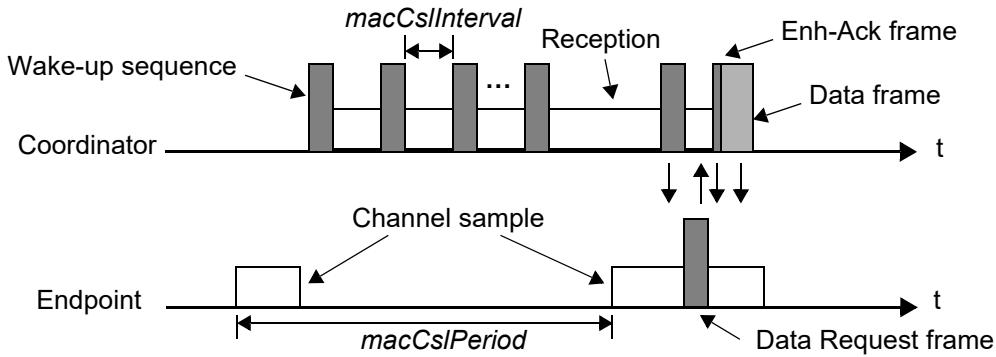


Figure 10-62—CSL operations when the wake-up frame interval is nonzero

If the destination address of the wake-up frame does not match *macShortAddress*, the CSL coordinator disables the receiver until the rendezvous time plus the transmission time of the maximum length payload frame and the secure Enh-Ack frame, and then resumes channel sampling.

10.5.4.3 CSL transmission

Each CSL transmission of a payload frame is preceded with a sequence of wake-up frames (wake-up sequence). The length of the wake up sequence is determined by *macCsMaxPeriod*, which can be zero.

10.5.4.4 Unicast transmission

In unicast transmissions, the wake-up sequence length may be long or short based on the following two cases:

Unsynchronized transmission: This is the case when the MAC sublayer does not know the CSL phase, and period of the destination device. In this case, the maximum wake-up sequence length is *macCsMaxPeriod*.

Synchronized transmission: This is the case when the MAC sublayer knows the CSL phase and period of the destination device. In this case, the wake-up sequence length is only the guard time against clock drift based on the last time when CSL phase and period updated about the destination device.

NOTE—Since the wake-up sequence is optional, the clock drift may be guarded by other means, like extension of a channel sample duration.

If the next higher layer has multiple frames to transmit to the same destination, it may set the Frame Pending field in the Frame Control field to one in all but the last frame, in order to maximize the throughput.

CSL unicast transmission is performed in the following steps by the MAC:

- For an unsynchronized transmission or any other than the first transmission in a sequence, perform CSMA-CA to acquire the channel. For the first synchronized transmission in a sequence perform single CCA to acquire the channel. CCA should be performed at the right time to transmit the frame right after the CCA procedure ends and at the channel sample.
- If the previous acknowledged frame to the destination has the Frame Pending field set and is within *macCsFramePendingWait*, as defined in Table 10-36, go to step e).
- If it is a synchronized transmission, wait until the destination device's next channel sample.

- d) For the duration of wake-up sequence length:
 - 1) Construct wake-up frame with the destination short address and remaining time to payload frame transmission (at the end of wake-up sequence).
 - 2) Transmit wake-up frame.
 - 3) If $macCslInterval$ is not equal to zero, wait for up to $macCslInterval$ for the data request frame from the corresponding destination device. If the data request frame is received, then stop the transmission of the wake-up sequence, perform a CSMA-CA to acquire the channel, and transmit an Enh-Ack frame with the Rendezvous Time field updated to zero.
- e) Transmit the frame.
- f) Wait for the Enh-Ack frame if the AR field of the received frame is set to one.
- g) If the Enh-Ack frame is received, update CSL phase and period information about the destination device from the CSL IE.
- h) If the Enh-Ack frame is not received, start retransmission process.

Retransmissions follow the same process as defined in 10.3.7.2 except that each transmission follows the previous process.

10.5.4.5 Broadcast transmission

Broadcast transmission is the same as unicast transmission except for the following conditions:

- It is always unsynchronized transmission.
- The destination address of the wake-up frames is set to the broadcast short address.
- If $macCslInterval$ is nonzero, the CSL coordinator will stop sending the wake-up sequence only after either receiving data request frames from all of the destination devices or when the $macCslMaxPeriod$ expires.
- It may include a CSL IE.

10.5.4.6 CSL reception

When a payload frame is received, the MAC layer performs the following steps:

- Immediately sends back an Enh-Ack frame with the destination address set as the transmitting device and its own CSL phase and period filled in the CSL IE. The Enh-Ack frame may be authenticated and/or encrypted depending on the current security mode.
- If the CSL IE is present in the received frame, the CSL phase and period information about the transmitting device is updated with the information in the CSL IE.
- Frame Pending field in the received frame is set to one, the receiver is kept on for $macCslFramePendingWait$ time before going back to CSL idle listening. Otherwise, CSL idle listening starts.

10.5.4.7 CSL over multiple channels

When $macCslChannelMask$ is nonzero, the CSL operations are extended to all the channels selected in the bitmap. CSL idle listening performs a channel sample on each channel from the lowest number to the highest in a round-robin fashion. In the unsynchronized case, CSL transmission transmits a wake-up sequence of the length number of channels \times $macCslMaxPeriod$ before each frame. In the synchronized case, CSL transmission calculates the next channel sample time and channel number and transmits at the next channel sample time on the right channel with a short wake-up sequence. In this case, CSL phase is the duration from now to the next channel sample on the first channel selected in $macCslChannelMask$.

10.5.4.8 Turning off CSL mode to reduce latency

The next higher layer has the option to turn off sampled listening and stop sending wake-up sequences to reduce latency for urgent messages. This assumes that the higher layer manages the coordination between the sender and receiver in turning on and off sampled listening. To turn off sampled listening, the next higher layer simply sets *macCslPeriod* to zero. To turn on sampled listening, the high layer restores *macCslPeriod* to its previous nonzero values. Similarly, to stop sending wake-up sequences, the next higher layer sets *macCslMaxPeriod* to zero and restores it to its previous value to return to normal CSL mode. To request a neighboring device to turn off sampled listening, the device shall send a frame to the device with frame pending bit set to one. This avoids CSL turning off the radio before the request is processed.

10.5.5 Header IEs for CSL

10.5.5.1 CSL IE

The CSL IE shall be used in all Enh-Ack frames if *macLeEnabled* is TRUE.

The CSL IE Content field shall be formatted as illustrated in Figure 10-63.

Octets: 2	2	0/2
CSL Phase	CSL Period	Rendezvous Time

Figure 10-63—CSL IE Content field format

The CSL Phase field shall be set to the CSL phase in units of 10 symbols.

The CSL Period field shall be set to the CSL period in units of 10 symbols.

The Rendezvous Time field is only present in the transmitted IE when *macCslInterval* is nonzero. The Rendezvous Time field contains the expected time, in units of 10 symbols, between the end of the transmission of the wake-up frame and the beginning of the transmission of the payload frame.

10.5.5.2 Rendezvous Time IE

The Rendezvous Time IE Content field shall be formatted as illustrated in Figure 10-64.

Octets: 2	2
Rendezvous Time	Wake-up Interval

Figure 10-64—Rendezvous Time IE Content field format

The Rendezvous Time field is the expected time in units of 10 symbols between the end of the transmission of the wake-up frame and the beginning of the transmission of the payload frame. The last wake-up frame in a wake-up sequence shall have the Rendezvous Time field set to the value zero.

The Wake-up Interval field is only present in the transmitted IE when *macCslInterval* is nonzero. The Wake-up Interval field is the length of the interval between two successive LE wake-up frames in the wake-up sequence, in units of 10 symbols. The Wake-up Interval field shall be set to *macCslInterval*.

10.5.6 Nested IEs for CSL

10.5.6.1 Hopping Timing IE

The Hopping Timing IE Content field shall be formatted as illustrated in Figure 10-65.

Octets: 3	2
Present Hop Time Offset	Hop Dwell Time

Figure 10-65—Hopping Timing IE Content field format

The Present Hop Time Offset field contains the amount of time in microseconds that has passed at the time of frame transmission since the transmitting device hopped to the present channel.

The Hop Dwell Time field shall be set to *macHopDwellTime* encoded as an unsigned integer.

10.5.7 MAC constants and PIB attributes for LE and CSL

LE and CSL specific attributes are described in Table 10-36.

Table 10-36—LE and CSL specific MAC PIB attributes

Attribute	Type	Range	Description	Default
<i>macCslPeriod</i>	Integer	0–0xffff	CSL sampled listening period in units of 10 symbols. Zero means always listening, i.e., CSL off.	0
<i>macCslMaxPeriod</i>	Integer	0–0xffff	Maximum CSL sampled listening period in units of 10 symbols in the entire PAN. It is set to zero to stop sending wake-up sequences. When it is not zero, this determines the length of the wake-up sequence when communicating to a device whose CSL listen period is unknown.	<i>macCslPeriod</i>
<i>macCslChannelMask</i>	Bitmap	—	32-bit bitmap relative to channels. It represents the list of channels CSL operates on. If bit is set then the channel is used. If this is zero then CSL operates on <i>phyCurrentChannelInfo</i> .	0x00000000
<i>macCslFramePending-Wait</i>	Integer	0x0000 or <i>macLifsPeriod</i> + max number of symbols per PPDU–0xffff	Number of symbols to keep the receiver on after receiving a payload frame with Frame Control field frame pending bit set to one.	—
<i>macLowEnergySuper-frameSupported</i>	Boolean	TRUE, FALSE	Indication of whether the low-energy superframe is operational or not. If this attribute is TRUE, the coordinator shall not transmit beacon frames regardless of <i>BO</i> value. This attribute shall be set to FALSE if the device is aware of the existence of allocated GTS.	—

Table 10-36—LE and CSL specific MAC PIB attributes (continued)

Attribute	Type	Range	Description	Default
<i>macLowEnergySuperframeSyncInterval</i>	Integer	0x0000–0xffff	Indication of beacon transmission interval when <i>macLowEnergySuperframeSupported</i> is TRUE. The beacon transmission interval shall be indicated by <i>macLowEnergySuperframeSyncInterval</i> times the beacon interval if this attribute is not zero. The beacon shall be transmitted only when requested if this attribute is zero.	—
<i>macCslInterval</i>	Integer	0–0xffff	Specifies the interval between two successive CSL wake-up frames in the wake-up sequence, in units of 10 symbols.	—

10.6 Receiver initiated transmission (RIT)

10.6.1 Overview of RIT

RIT allows receiving devices to periodically broadcast data request frames, and transmitting devices only transmit to a receiving device upon receiving a data request frame. RIT is suitable for the following application scenarios:

- Low data traffic rate and loose latency requirement, where a few seconds of latency is allowable by application.
- Local regulations restricting the duration of continuous radio transmissions.

10.6.2 Starting and maintaining PANs

10.6.2.1 RIT passive channel scan

The RIT passive scan is essentially the passive scan as described 6.4.1.2, but rather than discarding all frames that are not Beacon frames, the RIT passive scan discards all frames that are not RIT Data Request commands.

An RIT passive scan over a specified set of channels is requested using the MLME-SCAN.request primitive with the Valid Range of the ScanType parameter set to indicate RIT_PASSIVE. For each channel, the device shall set *phyCurrentChannelInfo* as per the MLME-SCAN.request primitive. After switching to the channel for an RIT passive scan, the device shall enable its receiver for at most the value of the ScanDuration parameter. During this time, the device shall reject all frames that are not RIT Data Request commands and record the information contained in all unique RIT Data Request commands in a PAN descriptor structure, as described in Table 8-3, including the channel information. A RIT Data Request command shall be assumed to be unique if it contains both a PAN ID and a source address that has not been seen before during the scan of the current channel.

If an RIT Data Request command is received when *macAutoRequest* is set to TRUE, the list of PAN descriptor structures shall be stored by the MAC sublayer until the scan is complete. When the scan is complete, the list shall be sent to the next higher layer in the PanDescriptorList parameter of the MLME-SCAN.confirm primitive.

If an RIT Data Request command is received when *macAutoRequest* is set to FALSE, each recorded PAN descriptor is sent to the next higher layer in a separate MLME-BEACON-NOTIFY.indication primitive, as described in 8.2.4.3. A received RIT Data Request command containing a nonzero-length payload shall also cause the PAN descriptor to be sent to the next higher layer via the MLME-BEACON-NOTIFY.indication primitive. Once the scan with *macAutoRequest* set to FALSE is complete, the MLME-SCAN.confirm shall be issued to the next higher layer with a null PanDescriptorList.

The RIT passive scan procedure is illustrated in Figure 10-66.

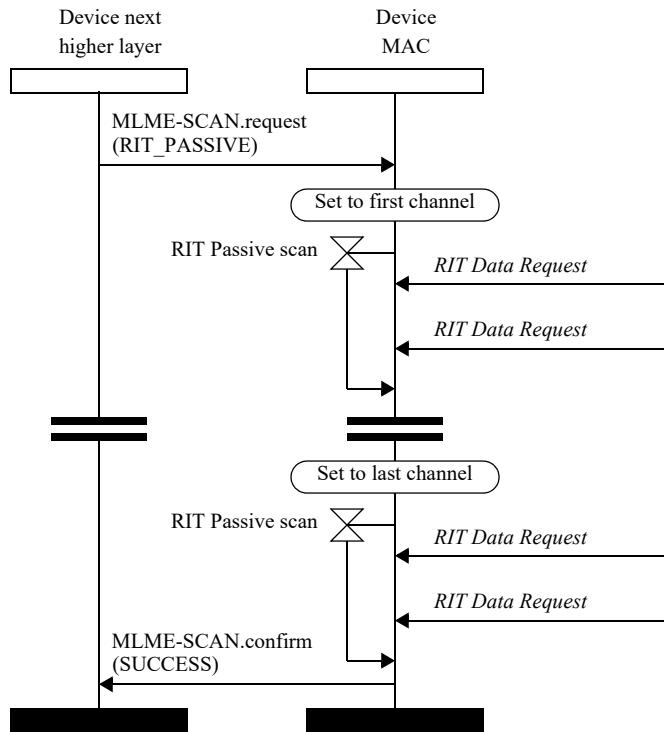


Figure 10-66—RIT Passive scan message sequence chart

10.6.3 Reception and transmission

10.6.3.1 General

RIT is an alternative low-energy MAC for PAN not using superframe structure. RIT mode is turned on when PIB attribute *macRitPeriod* is nonzero and is turned off when *macRitPeriod* is zero.

macCslPeriod (in coordinated sample listening) and *macRitPeriod* shall not be nonzero at the same time. Figure 10-67 illustrates the basic RIT operations. Figure 10-68 illustrates the RIT operations when the RIT Data Request command payload carries schedule information, as defined in 10.6.6.1.

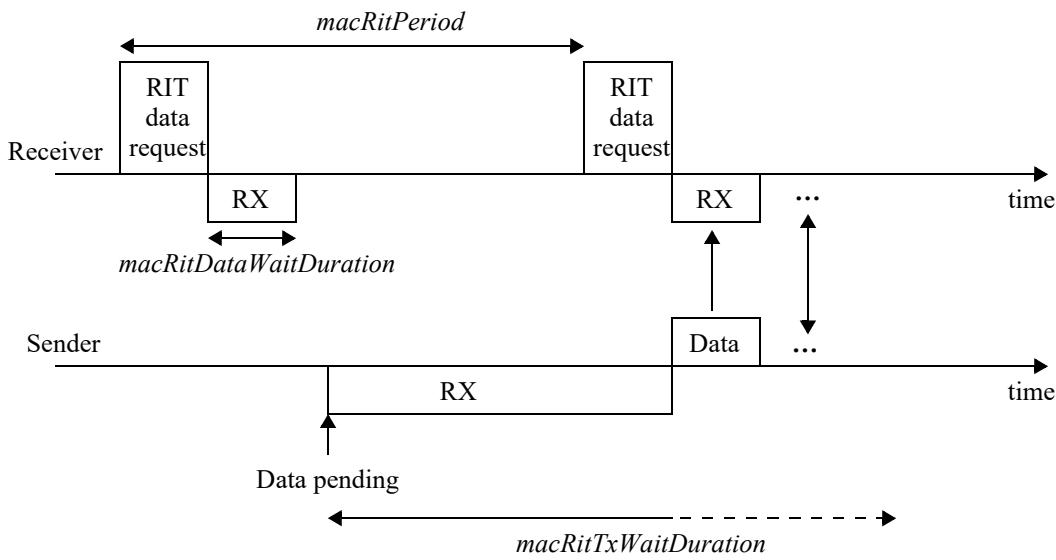


Figure 10-67—Basic RIT operations

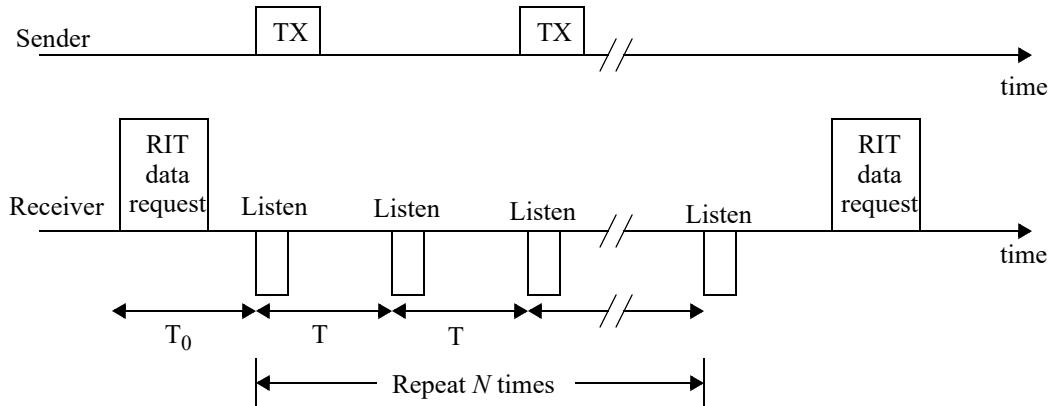


Figure 10-68—RIT operations when data request carries schedule information

10.6.3.2 Periodic RIT data request transmission and reception

In RIT mode, a device transmits an RIT Data Request command every *macRitPeriod* using unslotted CSMA-CA.

The destination address of the command may be broadcast short address or the address of the intended transmitter of data (associated coordinator). The command may optionally contain a payload, as defined in 10.6.6.1. When the command carries no payload, after the transmission of the RIT Data Request command, the device listens for *macRitDataWaitDuration* for an incoming frame (except for an RIT Data Request command) and then goes back to sleep state until the next periodic transmission of the RIT Data Request command. When a device is in the receiving state after transmission of the RIT Data Request command, an RIT Data Request command that is received from another device shall be discarded. When the RIT Data Request command carries the timing information as payload, the device goes back to sleep after the

transmission of the RIT Data Request command until the end of the Time to First Listen (T_0) period of time. Then the device repeats a listen interval of $macRitDataWaitDuration$ every Repeat Listen Interval (T) period of time for Number of Repeat Listen (N) times. The value of the Number of Repeat Listen field shall be less than $(macRitPeriod - \text{Time to First Listen field}) / (\text{Repeat Listen Interval field})$.

Upon reception of an RIT Data Request command with RIT Request Payload field, the device shall notify the next higher layer by issuing an MLME-RIT-REQ.indication, as defined in 10.6.7.1.

Figure 10-69 shows the message sequence chart for starting RIT mode.

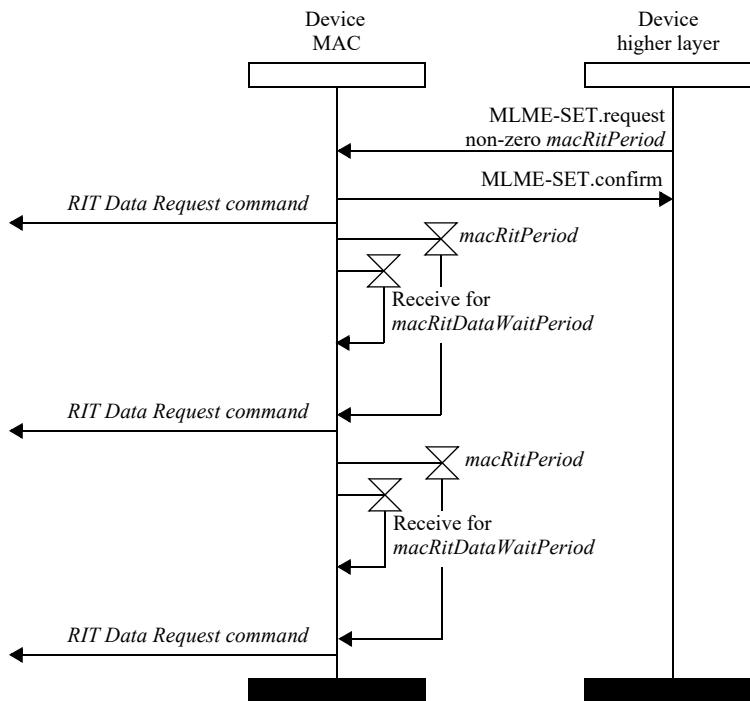


Figure 10-69—Message sequence chart for starting RIT mode

The device shall start listening slightly before each scheduled listen time based on a guard time computed from possible clock skew since the last RIT Data Request command transmission.

Upon reception of frame after the transmission of the RIT Data Request command, the device notifies its arrival to the next higher layer by initiating a corresponding indication primitive. At the completion of frame reception, the next higher layer may set $macRitPeriod$ to zero (RIT off). If this is the case, the device shall stop periodic transmission of RIT Data Request commands and become always active until $macRitPeriod$ is set to a nonzero value by the next higher layer. During this period when RIT is off, all transactions shall be handled as those of normal PANs not using superframe structure.

Figure 10-70 shows the message sequence chart for RIT mode when the RIT Data Request command contains a payload.

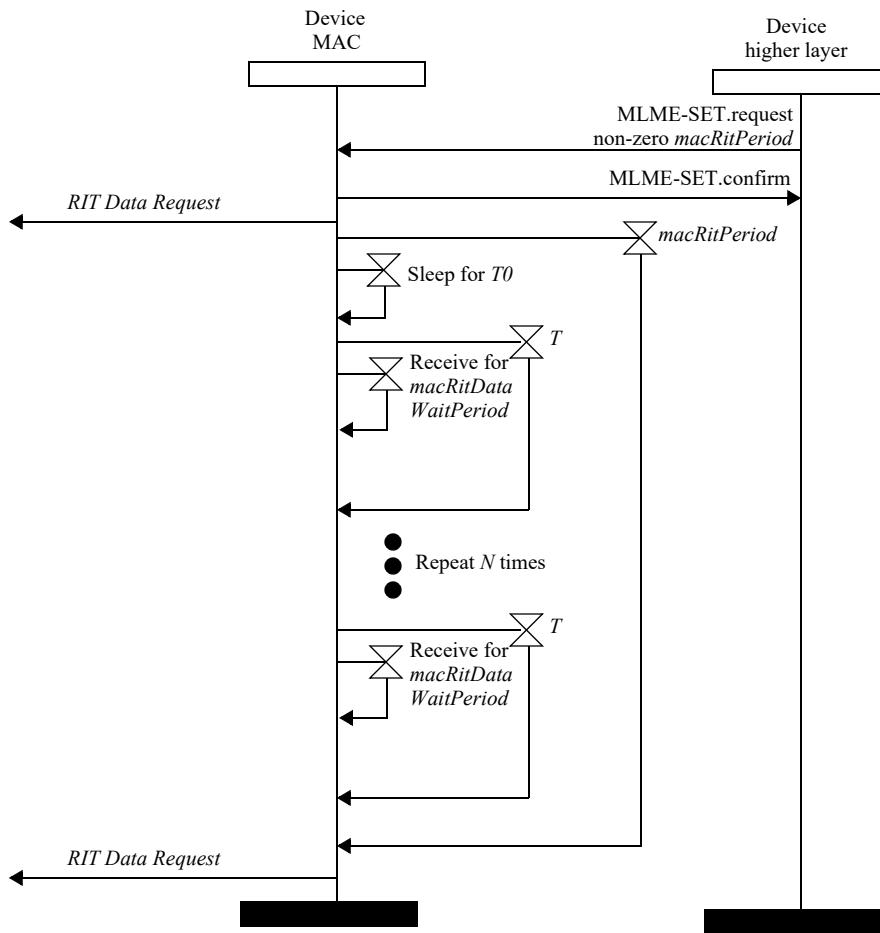


Figure 10-70—Message sequence chart for RIT with the RIT Data Request carrying a payload

10.6.3.3 RIT transmission

In order to transmit a frame in RIT mode, the device may stop its periodic transmission of RIT Data Request commands, enable its receiver, and wait at most $macRitTxWaitDuration$ for reception of an RIT Data Request command from another device.

Upon reception of an RIT Data Request command, the MAC sublayer sends the pending data using unslotted CSMA-CA. The Destination PAN ID field and the Destination Address field of the outgoing Data frame shall be set as the Source PAN ID field and the Source Address field of the received RIT Data Request command, respectively. At the completion of frame transmission, the corresponding confirm primitive shall be issued by the MAC sublayer to the next higher layer. At this point, the device shall restart its transmission of periodic RIT Data Request commands. If the next higher layer sets the $macRitPeriod$ parameter to RIT off, the device shall stop periodic transmission of RIT Data Request commands and become active.

When the RIT Data Request commands carry the Listen Information field, the device may either wait to receive a data request frame from the receiving device, or sleep until the next scheduled listen time by the receiving device and then wake up to transmit the intended frame.

Figure 10-71 shows the message sequence chart for data transmission in RIT mode.

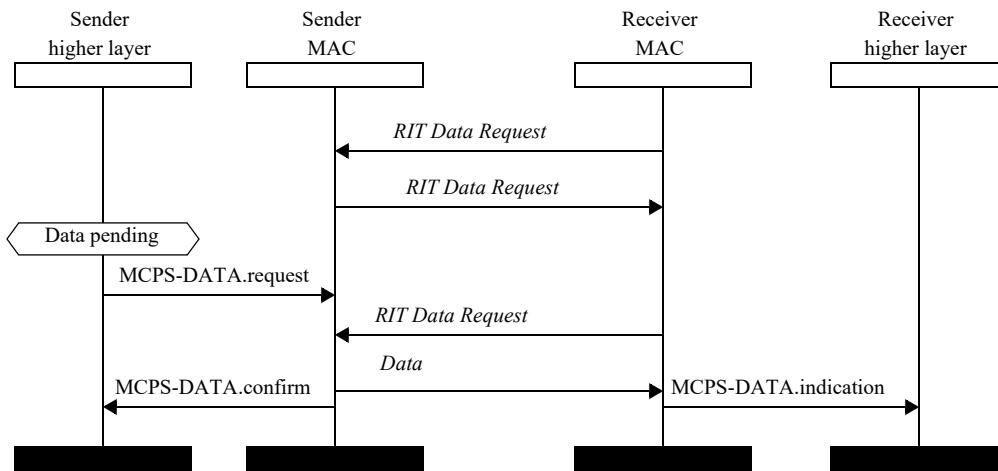


Figure 10-71—Message sequence chart for data transmission in RIT mode

When the RIT Data Request command contains an RIT Request Payload field, the MLME shall issue an MLME-RIT-REQ.indication, as defined in 10.6.7.1. The higher layer may respond with the MLME-RIT-RES.request, as defined in 10.6.7.2.

Optionally, for the devices operating in 920 MHz band, a sender device may skip doing CSMA-CA for transmission of an RIT Data Response command as long as it complies with the regulatory requirements.

Figure 10-72 shows the message sequence chart for data transmission in RIT Mode with RIT Request Payload field and using an RIT Data Response command.

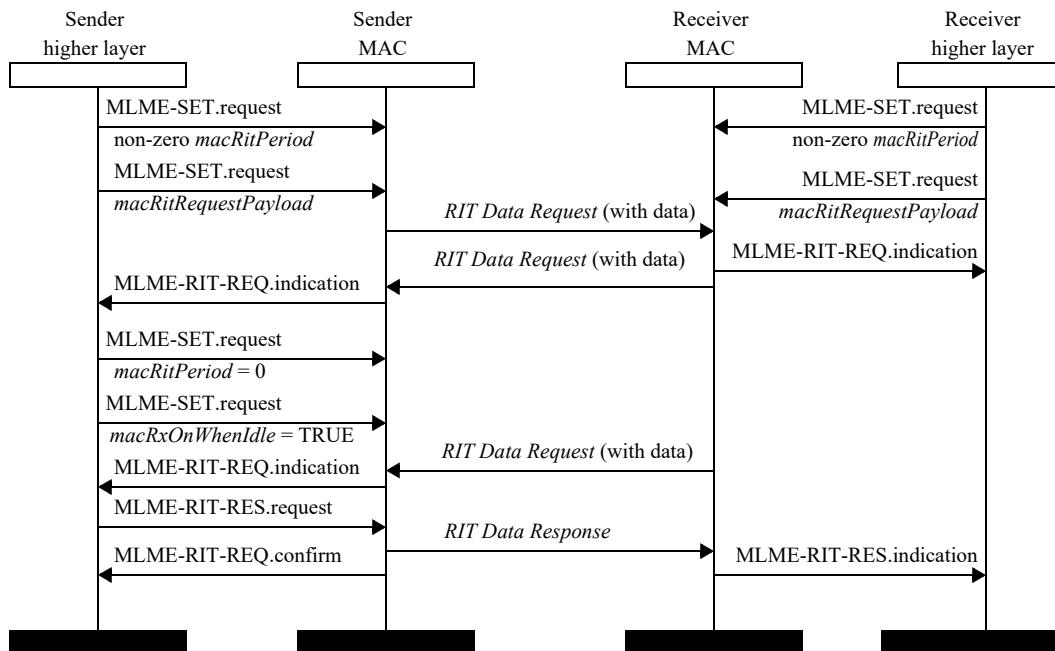


Figure 10-72—Message sequence chart for data transmission in RIT mode with RIT Response Payload field

10.6.4 Implicit receiver initiated transmission (I-RIT)

Implicit receiver initiated transmission (I-RIT) is a low energy mode for PANs not using superframe structure. I-RIT is designed to be used by end devices, such as sensors, that primarily transmit information to a coordinator but have no way of determining when they should make use of conventional RIT.

In order to enable I-RIT in an end device, the PIB attribute *macIRitEnabled* is set to TRUE. When an end device has I-RIT enabled, the device shall enable its receiver *macIRitOffsetInterval* after the last bit of its transmitted frame for a period of *macIRitListenDuration*, in order to allow the receipt of a frame from the coordinator. The values of *macCslPeriod* and *macCslInterval* shall be ignored when *macIRitEnabled* is TRUE. Transmission and reception in I-RIT mode is illustrated in Figure 10-73.

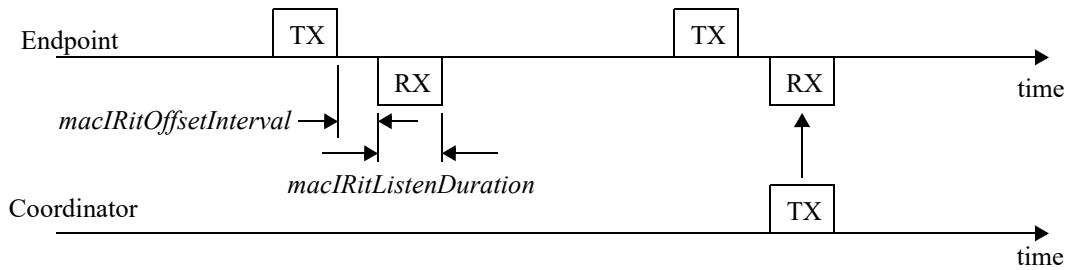


Figure 10-73—I-RIT transmission

10.6.5 Header IEs for RIT

10.6.5.1 RIT IE

The RIT IE Content field shall be formatted as illustrated in Figure 10-74. The use of the RIT IE is described in 10.2.4.

Octets: 1	1	2
Time to First Listen	Number of Repeat Listen	Repeat Listen Interval

Figure 10-74—RIT IE Content field format

The Time to First Listen field shall be set to the time interval in units of *aBaseSuperframeDuration*, until the first time that the device will be receiving, as defined in 10.6.3.2.

The Number of Repeat Listen field shall be set to the number of times that the listening interval will be repeated, as defined in 10.6.3.2.

Repeat Listen Interval shall be set to the time interval, in units of *aBaseSuperframeDuration*, between subsequent intervals during which the device will be in receiving, as defined in 10.6.3.2.

10.6.6 MAC commands for RIT

10.6.6.1 RIT Data Request command

The RIT Data Request command shall only be sent by a device supporting RIT mode.

The Frame Pending field of the Frame Control field shall be set to zero and ignored upon reception, and the AR field shall also be set to zero. All other fields shall be set appropriately according to the intended use of the command.

The RIT Data Request command Content field shall be formatted as illustrated in Figure 10-75.

Octets: variable
Listen Information/RIT Payload

Figure 10-75—RIT Data Request command Content field format

If the Content field is present and the first octet of the Content field is 0xff, then the Content field contains the RIT Payload field. Otherwise, if the Content field is present and the first octet is not 0xff, then the Content field contains the List Information field.

The List Information field, when present, shall be formatted as illustrated in Figure 10-76.

Octets: 1	1	2
Time to First Listen	Number of Repeat Listen	Repeat Listen Interval

Figure 10-76—Format of the Listen Information field

Time to First Listen field is defined in 10.6.5.1. The value 0xff shall not be used for the Time to First Listen field.

The Number of Repeat Listen field is defined in 10.6.5.1.

The Repeat Listen Interval field is defined in 10.6.5.1.

The RIT Payload field shall be included if and only if *macRitRequestPayload* is nonzero length. The RIT Payload field, when present, shall be formatted as illustrated in Figure 10-77.

Octets: 1	variable
0xff	RIT Request Payload

Figure 10-77—Format of the RIT Payload field

The RIT Request Payload field shall be set to the value of *macRitRequestPayload*.

10.6.6.2 RIT Data Response command

The RIT Data Response command shall only be sent by a device supporting RIT mode.

The Frame Pending field of the Frame Control field shall be set to zero and ignored upon reception, and the AR field shall also be set to zero. All other fields shall be set appropriately according to the intended use of the command.

The RIT Data Response command Content field shall be formatted as illustrated in Figure 10-78.

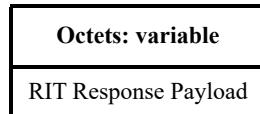


Figure 10-78—RIT Data Response command Content field format

The RIT Response Payload field contains RitResponsePayload received in an MLME-RIT-RES.request primitive. The field is passed as received from the higher layer; no octet ordering changes shall be made.

10.6.7 MAC management service primitives for RIT

10.6.7.1 MLME-RIT-REQ.indication

This primitive reports the reception of an RIT Data Request command with RIT Request Payload field.

The semantics of this primitive are as follows:

```

MLME-RIT-REQ.indication      (
    SrcAddrMode,
    SrcPanId,
    SrcAddr,
    DstAddrMode,
    DstPanId,
    DstAddr,
    RitRequestPayload,
    HeaderleList,
    PayloadleList,
    LinkQuality,
    Dsn,
    Timestamp,
    SecurityParams
)
  
```

The primitive parameters are defined in Table 10-37.

Table 10-37—MLME-RIT-REQ.indication parameters

Name	Type	Valid range	Description
SrcAddrMode	Enumeration	NONE, SHORT, EXTENDED	The source addressing mode of the frame that was received.
SrcPanId	Integer	0x0000–0xffff	The Source PAN ID from the frame that was received. Valid only when a source PAN ID is included in the received frame.
SrcAddr	—	As specified by the SrcAddrMode parameter	The source address of the frame that was received.
DstAddrMode	Enumeration	NONE, SHORT, EXTENDED	The destination addressing mode of the frame that was received.

Table 10-37—MLME-RIT-REQ.indication parameters (continued)

Name	Type	Valid range	Description
DstPanId	Integer	0x0000–0xffff	The Destination PAN ID from the frame that was received. Set to the receiver's PAN ID if the PAN ID is not carried in the received frame.
DstAddr	—	As specified by the DstAddrMode parameter	The destination address of the frame that was received.
RitRequestPaylo ad	Set of octets	—	The set of octets from the RIT Request Payload field in the frame that was received.
HeaderIeList	List of header IEs as described in 7.4.2	—	The header IEs, excluding Termination IEs, that were included in the frame. If empty, then no header IEs were in the frame.
PayloadIeList	List of payload IEs as described in 7.4.3	—	The payload IEs, excluding Termination IEs, that were included in the frame. If empty, then no payload IEs were in the frame.
LinkQuality	Integer	0x00–0xff	LQI value measured during reception of the RIT Data Request command. Lower values represent lower LQI, as described in 11.2.7.
Dsn	Integer	0x00–0xff	The DSN of the received RIT Data Request command, if one was present.
Timestamp	Integer	0x000000–0xffffffff	The time at which the command was received. The format of timestamp is specified in 6.5.3.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

This primitive is generated by the MLME of a device and issued to its next higher layer upon the reception of an RIT Data Request command containing an RIT Request Payload field.

10.6.7.2 MLME-RIT-RES.request

This primitive allows the next higher layer of a device to respond to the MLME-RIT-RES.indication primitive.

The semantics of this primitive are as follows:

```
MLME-RIT-RES.request ( 
    SrcAddrMode,
    DstAddrMode,
    DstPanId,
    DstAddr,
    RitResponsePayload,
    HeaderIeList,
    PayloadIeList,
    HeaderIeIdList,
    NestedIeIdList,
    AckTx,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-38.

Table 10-38—MLME-RIT-RES.response parameters

Name	Type	Valid range	Description
SrcAddrMode	Enumeration	NONE, SHORT, EXTENDED	The source addressing mode for this frame.
DstAddrMode	Enumeration	NONE, SHORT, EXTENDED	The destination addressing mode for this frame.
DstPanId	Integer	0x0000–0xffff	The PAN ID of the entity to which the frame is being transferred.
DstAddr	—	As specified by the DstAddrMode parameter	The address of the entity to which the frame is being transferred.
RitResponsePayload	Set of octets	—	The set of octets forming the RIT Response Payload field in the frame.
HeaderIeList	Set of IEs as described in Table 7-7	As defined in Table 7-7	The header IEs, excluding Termination IEs, that are to be included with the frame in addition to any header IEs added by the MAC. If empty, no additional header IEs are to be included.
PayloadIeList	Set of IEs as described in Table 7-8	As defined in Table 7-8	The payload IEs, excluding Termination IEs, that are to be included with the frame in addition to any payload IEs added by the MAC. If empty, no additional payload IEs are to be included.
HeaderIeIdList	List of header IE IDs, as described in Table 7-7	—	The IDs of header IEs, excluding Termination IEs, to be added to the frame. The MAC will provide the content for the IE.
NestedIeSubIdList	List of Nested IE sub-IDs, as described in Table 7-9 and Table 7-10	—	The sub-IDs of nested IEs, excluding Termination IEs, to be added to the Data frame. The MAC will provide the content for the IE.
AckTx	Boolean	TRUE, FALSE	TRUE if acknowledged transmission is used, FALSE otherwise.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

If the MLME-RIT-RES.request primitive has invalid parameters, the MLME will issue an MLME-RIT-RES.confirm primitive with Status set to INVALID_PARAMETER and take no further action.

Otherwise, the MLME of the device shall generate an RIT Data Response command, as described in 10.6.6.2. If the acknowledgment is received for the command, the MLME shall issue an MLME-RIT-RES.confirm primitive with Status set to SUCCESS. If the number of retries is exceeded and an acknowledgment is not received, the MLME shall issue an MLME-RIT-RES.confirm primitive with Status set to NO_ACK.

10.6.7.3 MLME-RIT-RES.indication

This primitive reports the reception of an RIT Data Response command.

The semantics of this primitive are as follows:

```
MLME-RIT-RES.indication      (
    SrcAddrMode,
    SrcPanId,
    SrcAddr,
    DstAddrMode,
    DstPanId,
    DstAddr,
    RitResponsePayload,
    HeaderIeList,
    PayloadIeList,
    LinkQuality,
    Dsn,
    Timestamp,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-39.

Table 10-39—MLME-RIT-RES.indication parameters

Name	Type	Valid range	Description
SrcAddrMode	Enumeration	NONE, SHORT, EXTENDED	The source addressing mode of the frame that was received.
SrcPanId	Integer	0x0000–0xffff	The Source PAN ID from the frame that was received. Valid only when a source PAN ID is included in the received frame.
SrcAddr	—	As specified by the SrcAddrMode parameter	The source address of the frame that was received.
DstAddrMode	Enumeration	NONE, SHORT, EXTENDED	The destination addressing mode of the frame that was received.
DstPanId	Integer	0x0000–0xffff	The Destination PAN ID from the frame that was received. Set to the receiver's PAN ID if the PAN ID is not carried in the received frame.
DstAddr	—	As specified by the DstAddrMode parameter	The destination address of the frame that was received.
RitResponsePayload	Set of octets	—	The set of octets from the RIT Response Payload field in the frame that was received.
HeaderIeList	List of header IEs as described in 7.4.2	—	The header IEs, excluding Termination IEs, that were included in the frame. If empty, then no header IEs were in the frame.
PayloadIeList	List of payload IEs as described in 7.4.3	—	The payload IEs, excluding Termination IEs, that were included in the frame. If empty, then no payload IEs were in the frame.

Table 10-39—MLME-RIT-RES.indication parameters (continued)

Name	Type	Valid range	Description
LinkQuality	Integer	0x00–0xff	LQI value measured during reception of the RIT Data Request command. Lower values represent lower LQI, as described in 11.2.7.
Dsn	Integer	0x00–0xff	The sequence number of the received RIT Data Request command, if one was present.
Timestamp	Integer	0x000000–0xffffffff	The time at which the command was received. The format of timestamp is specified in 6.5.3.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

This primitive is generated by the MLME of a device and issued to its next higher layer upon the reception of an RIT Data Response command.

10.6.7.4 MLME-RIT-RES.confirm

This primitive reports the result of a request to send an RIT Data Response command.

The semantics of this primitive are as follows:

```
MLME-RIT-Data-Response.confirm ( 
    Status
)
```

The primitive parameter is defined in Table 10-40.

Table 10-40—MLME-RIT-RES.confirm parameter

Name	Type	Valid Range	Description
Status	Enumeration	SUCCESS, also see 8.2.2	The status of MLME-RIT-RES.request primitive.

The value of the Status parameter is set as described in 10.6.7.2.

10.6.8 MAC constants and PIB attributes for RIT

RIT-specific attributes are described in Table 10-41.

Table 10-41—RIT specific MAC PIB attributes

Attribute	Type	Range	Description	Default
<i>macRitPeriod</i>	Integer	0x000000–0xffffffff	The interval (in unit periods) for periodic transmission of RIT Data Request commands in RIT mode. The unit period is <i>aBaseSuperframeDuration</i> . A value of zero indicates that RIT is off.	0
<i>macRitDataWaitDuration</i>	Integer	0x00–0xff	The maximum time (in unit periods) to wait for Data frame after transmission of RIT Data Request command in RIT mode. The unit period is <i>aBaseSuperframeDuration</i> .	0
<i>macRitTxWaitDuration</i>	Integer	<i>Period</i> –0xffffffff	The maximum time (in unit periods) that a transaction is stored by a device in RIT mode. The unit period is <i>aBaseSuperframeDuration</i> .	0
<i>macRitRequestPayload</i>	Set of octets	—	The payload to include an RIT Data Request command.	
<i>macIRitOffsetInterval</i>	Integer	0x0000–0xffff	A value of zero indicates that I-RIT is disabled. A nonzero value specifies the interval, in symbol periods, from the end of the transmitted frame to the beginning of the I-RIT listening period.	0x00
<i>macIRitListenDuration</i>	Integer	0x00–0xff	The duration of listening time, in symbol periods, for which the receiver is listening for the beginning of a frame to receive.	0x64
<i>macIRitEnabled</i>	Boolean	TRUE, FALSE	If TRUE, the I-RIT mode of operation is enabled, as described in 10.6.4. If FALSE, the I-RIT mode of operation is disabled.	FALSE

10.7 Television white space (TVWS)

10.7.1 General

TVWS operation has the requirement to determine which TVWS frequency allocations are available for use at a given time and geographic location. TVWS devices need to have access to TVWS channel availability information, for example, via a central database that is accessed over the Internet. A TVWS device that has no connection to the Internet has to depend upon another TVWS device that has access to the TVWS database via the Internet to acquire channel availability information.

In certain regulatory domains, an independent device operating in TVWS is required to communicate with a database which stores information on operation of primary incumbent systems to obtain permission and radio resource information, prior to starting communications. This database to protect primary systems is typically, but not limited to, a geolocation database (GDB). When a GDB is employed as the database, an independent device first communicates with the GDB to obtain permission to operate in TVWS. The communication between the independent device and the GDB is outside the scope of this standard. In this case, the independent device determines its geolocation to be reported to the GDB. The GDB then provides available channels and relevant operating information. Upon receiving permission from the GDB, the

independent device may start a network and begin enabling other devices. Figure 10-79 shows the state transition diagram of the enabling procedure for a dependent device.

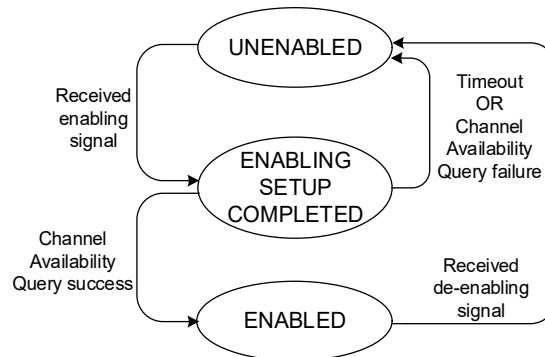


Figure 10-79—State transition of a dependent device

A dependent device, prior to receiving channel availability information (such as at power on or reset condition) begins in the UNENABLED state. The device may perform a channel scan or other procedure to detect transmissions that are active on the channel and determine a suitable source of channel availability data (e.g., an independent device advertisement). Upon receiving a frame with the TVWS Channel Information Source IE, as defined in 10.7.3.7, from an independent device, the state transitions to ENABLING SETUP COMPLETED. From the ENABLING SETUP COMPLETED state, the dependent device will initiate the exchange of information in order to be enabled, as required by the particular regulatory domain in which it is operating. The information exchange is facilitated by several IEs as specified in 10.7.3.3 and 10.7.3.4. Information on the list of locations of particular valid channels is contained in the IE specified in 10.7.3.5. Information on the set of available channels is contained in the IE specified in 10.7.3.6. A device that has access to channel availability information advertises that fact using the TVWS Channel Information Source IE as specified in 10.7.3.7. Upon successfully completing a channel availability query, the state transitions to ENABLED. In this state, the dependent device is able to conduct data communications.

10.7.2 Channel timing management (CTM)

CTM facilitates assessment of the available timing schedule when a channel is available. CTM is used by employing the CTM IE as in 10.7.3.8. Upon receipt of MLME-CTM.request, the MLME shall schedule transmission for a CTM IE as in 10.7.3.8. The CTM IE may be contained in an Enhanced Beacon frame.

A device transmits a CTM IE to a PAN coordinator that is capable of database access as indicated in the enabling signal. The PAN coordinator capable of database access visits the database and obtains the channel timing information for available channels. The PAN coordinator may respond to a request by sending the CTM IE with CTM Control field set to Request Declined, to indicate that it has no capability to provide schedule information.

A device may transmit a CTM IE to request channel information from another device. A device shall respond to a CTM IE request using a CTM IE with the CTM Control field set to Success if it is capable of providing channel timing information on WPAN channels obtained from a database. Otherwise it shall respond with the CTM Control field set to Request Declined, to indicate that it has no capability to provide schedule information on available channels due to various reasons.

When the information in a CTM IE is identical to the information in the most recently transmitted CTM IE to the same requesting device, the responding device may set the CTM Control field value in a query

response to Successful with no channel schedule changes from the last query and leave the Channel Timing Information field empty.

10.7.3 Nested IEs for TVWS

10.7.3.1 TVWS PHY Operating Mode Description IE

The TVWS PHY Operating Mode Description IE Content field shall be formatted as shown in Figure 10-80. The values in the TVWS PHY Operating Mode Description IE correspond to those values that will take effect after the PHY change operation, as described in 10.26.

Bits: 0–7	8–15	16–17	18–31	32–71
Band ID	PHY Channel ID	PHY Type Selector	Operating Parameters	Available Frequency Range

Figure 10-80—TVWS PHY Operating Mode Description IE Content field format

The Band ID field contains the bit number of the matching Band ID in Table 10-48.

The PHY Channel ID field contains channel number, *NumChan*, for the TVWS PHY channel as defined in 11.1.3.9.

The PHY Type Selector field indicates which TVWS PHY is described in the Operating Parameters field. Valid values for the PHY Type Selector field are given in Table 10-42.

Table 10-42—PHY Type Selector field values

Field value	PHY type
0	TVWS FSK PHY
1	TVWS OFDM PHY
2	TVWS NB OFDM PHY
3	Reserved

The Operating Parameters field for a TVWS FSK PHY shall be formatted as shown in Figure 10-81.

Bits: 0	1–2	3	4	5	6–8	9	10	11–13
FEC	FEC scheme	Interleaving	Spreading	Data Whitening	Mode	Modulation Index	SFD Length	Reserved

Figure 10-81—Operating Parameters field format for TVWS FSK PHY

The forward error correction (FEC) field shall be set to one if FEC is enabled and shall be set to zero otherwise.

The FEC Scheme field indicates the type of FEC that will be used. When the FEC field is set to zero, the FEC Scheme field is reserved. Valid values of the FEC Scheme field are given in Table 10-43.

Table 10-43—FEC Scheme field values

Field value	FEC Scheme used (as defined in 25.2.3)
0	First FEC scheme
1	Second FEC scheme
2	Third FEC scheme
3	Reserved

The Interleaving field shall be set to one if interleaving is enabled and shall be set to zero otherwise.

NOTE—The Interleaving field is reserved if FEC is not enabled or the FEC Scheme field value is not one.

The Spreading field shall be set to one if spreading is enabled and shall be set to zero otherwise.

The Data Whitening field shall be set to one if data whitening is enabled and shall be set to zero otherwise.

The Mode field shall be set to the TVWS FSK mode, as defined in Table 25-3, that is used.

For Mode field values of one, two, or three, the Modulation Index field shall be set to zero for a modulation index of 0.5 and shall be set to one for a modulation index of 1.0. For all other values of the Mode field, the Modulation Index field is reserved.

The start-of-frame delimiter (SFD) Length field shall be set to zero for a 16-bit SFD and shall be set to one for a 24-bit SFD.

The Operating Parameters field for a TVWS OFDM PHY shall be formatted as illustrated in Figure 10-82.

Bits: 0–1	2–4	5–13
Modulation	MCS Mode	Reserved

Figure 10-82—Operating Parameters field format for TVWS OFDM PHY

The Modulation field specifies the modulation that is used. Valid values for the Modulation field are given in Table 10-44.

Table 10-44—Modulation field values

Field value	Modulation type
0	BPSK
1	QPSK
2	16-QAM
3	Reserved

The MCS Mode field shall be set to one of the non-reserved values in Table 10-45.

Table 10-45—MCS Mode field values for TVWS OFDM

MCS Mode field	MCS
0	Reserved
1	MCS 1
2	MCS 2
3	MCS 3
4	MCS 4
5	MCS 5
6–7	Reserved

The Operating Parameters field for a TVWS NB OFDM PHY shall be formatted as shown in Figure 10-83.

Bits: 0–3	4	5–13
MCS Mode	Channel Aggregation	Reserved

Figure 10-83—Operating Parameters field format for TVWS NB OFDM PHY

The MCS Mode field shall be set to one of the non-reserved values in Table 10-46.

Table 10-46—MCS Mode field values for TVWS NB OFDM

MCS Mode field	MCS
0	Reserved
1	MCS 1
2	MCS 2
3	MCS 3
4	MCS 4
5	MCS 5
6	MCS 6
7	MCS 7
8	MCS 8
9–15	Reserved

The Channel Aggregation field shall be set to one if channel aggregation is enabled and shall be set to zero otherwise.

The Available Frequency Range field shall be only be present when the Band ID field value is less than or equal to five. The Available Frequency Range field shall be formatted as illustrated in Figure 10-100 with field values described in 10.7.3.6.

10.7.3.2 TVWS Device Capabilities IE

The presence of this IE in a transmitted frame indicates that the device supports operation of a TVWS PHY. The TVWS Device Capabilities IE Content field shall be formatted as shown in Figure 10-84.

Octets: 1	3	3	variable
TVWS PHY Type	Supported Bands	TVWS Supported PHY Features	TVWS Supported Channels

Figure 10-84—TVWS Device Capabilities IE

The TVWS PHY Type field indicates the PHY type being described in the IE. Valid values of the TVWS PHY Type field shall be set to one of the non-reserved values shown in Table 10-47.

Table 10-47—TVWS PHY Type field values

Value	Description
0	TVWS-FSK
1	TVWS-OFDM
2	TVWS-NB-OFDM
3–255	Reserved

The Supported Bands field is a bitmap indicating the bands, as defined in Table 11-1, supported by the device. A value of one indicates that the band is supported, and zero indicates the band is not supported. The supported bands shall be encoded as shown in Table 10-48. The device shall indicate only those bands that are implemented and defined for the indicated PHY type.

Table 10-48—Supported Bands field values

Bit number	Band ID
0	TVWS Band USA
1	TVWS Band UK
2	TVWS Band Japan
3	TVWS Band Canada
4	TVWS Band Korea
5	TVWS Band EU
6	450 MHz
7	470 MHz
8	780 MHz
9	863 MHz
10	896 MHz
11	901 MHz

Table 10-48—Supported Bands field values (continued)

Bit number	Band ID
12	915 MHz
13	917 MHz
14	928 MHz
15	920 MHz
16	Reserved
17	2450 MHz
18–23	Reserved

The TVWS Supported PHY Features field indicates the supported features of a TVWS PHY. The content depends on the value of the TVWS PHY Type field.

The Supported Features field for TVWS FSK PHY shall be formatted as shown in Figure 10-85.

Bits: 0	1–4	5–8	9	10	11	12	13–20	21–23
24-bit SFD Length	FEC Scheme	Spreading Factor	Data Whitening	Alternating Spreading Pattern	Non-alternating Spreading Pattern	Ranging	Operating Mode	Reserved

Figure 10-85—TVWS FSK PHY Supported Features field format

The 24-bit SFD Length field shall be set to one if the 24-bit SFD length is supported and shall be set to zero otherwise.

The FEC Scheme field is a bitmap that indicates if an FEC scheme is supported. Valid values are given in Table 10-49.

Table 10-49—FEC Scheme field valid values

Bit number	Description
1	First FEC scheme as defined in 25.2.3
2	Second FEC scheme as defined in 25.2.3
3	Interleaver for the second FEC scheme as defined in 25.2.3
4	Third FEC scheme as defined in 25.2.3

The Spreading Factor field is a bitmap that indicates if a spreading factor is supported. Valid values are given in Table 10-50.

The Data Whitening field shall be set to one if data whitening is supported and shall be set to zero otherwise.

Table 10-50—Spreading Factor field valid values

Bit number	Description
5	Spreading factor 2 supported
6	Spreading factor 4 supported
7	Spreading factor 8 supported
8	Spreading factor 16 supported

The Alternating Spreading Pattern field shall be set to one if alternating spreading patterns are supported and shall be set to zero otherwise.

The Non-alternating Spreading Pattern field shall be set to one if non-alternating spreading patterns are supported and shall be set to zero otherwise.

The Ranging field shall be set to one if ranging is supported and shall be set to zero otherwise.

The Operating Mode field is a bit map that indicates if a particular operating mode is supported. Valid values of the operating mode field are given in Table 10-51.

Table 10-51—Operating Mode field valid values

Bit number	Description
13	Mode#1 with modulation index = 0.5
14	Mode#1 with modulation index = 1
15	Mode#2 with modulation index = 0.5
16	Mode#2 with modulation index = 1
17	Mode#3 with modulation index = 0.5
18	Mode#3 with modulation index = 1
19	Mode#4
20	Mode#5

The Supported Features field for TVWS OFDM PHY shall be formatted as shown in Figure 10-86.

Bits: 0	1	2	3–6	7	8–23
MCS3	MCS4	MCS 5	Number of STF Symbols	Ranging	Reserved

Figure 10-86—TVWS-OFDM PHY Supported Features field format

The MCS3 field shall be set to one if MCS3, as defined in 26.3, is supported and shall be set to zero otherwise.

The MCS4 field shall be set to one if MCS4, as defined in 26.3, is supported and shall be set to zero otherwise.

The MCS5 field shall be set to one if MCS5, as defined in 26.3, is supported and shall be set to zero otherwise.

The Number of short training field (STF) Symbols field shall be set to the maximum number of STF symbols, as defined in 26.2.2, supported by the device during reception.

The Ranging field shall be set to one if ranging is supported and shall be set to zero otherwise.

The Supported Features field for TVWS NB OFDM PHY shall be formatted as shown in Figure 10-87.

Bits: 0	1	2	3	4	5	6	7	8-23
Channel Aggregation	Cyclic prefix 1/16	Cyclic prefix 1/8	Guard Interval 1/16	Guard Interval 1/8	Symbol Interval 1/16	Symbol Interval 1/8	Ranging	Reserved

Figure 10-87—TVWS NB OFDM PHY Supported Features field format

The Channel Aggregation field shall be set to one if channel aggregation is supported and shall be set to zero otherwise.

The Cyclic Prefix 1/16 field shall be set to one if a 1/16 cyclic prefix is supported and shall be set to zero otherwise.

The Cyclic Prefix 1/8 field shall be set to one if a 1/8 cyclic prefix is supported and shall be set to zero otherwise.

The Guard Interval 1/16 field shall be set to one if a 1/16 guard interval is supported and shall be set to zero otherwise.

The Guard Interval 1/8 field shall be set to one if a 1/8 guard interval is supported and shall be set to zero otherwise.

The Symbol Interval 1/16 field shall be set to one if a 1/16 symbol interval is supported and shall be set to zero otherwise.

The Symbol Interval 1/8 field shall be set to one if a 1/8 symbol interval is supported and shall be set to zero otherwise.

The Ranging field shall be set to one if ranging is supported and shall be set to zero otherwise.

The Channels Supported field is a set of channel lists that shall be formatted as described in Figure 10-88.

Octets: 1/variable	1/variable	...	1/variable
Channel List for Band 1	Channel List for Band 2	...	Channel List for Band <i>n</i>

Figure 10-88—TVWS Supported Channels field format

The TVWS Supported Channels field content depends on the value of the Supported Bands field. For each defined band, the channel numbering is given in Table 10-48. For each band indicated as supported, a corresponding Channel List for Band field map shall be included. Each Channel List for Band field shall be encoded as shown in Figure 10-89. The first bit field of each map indicates whether all channels in that band are supported. If this field is set to one, then all channels defined for the band in Table 10-48 are supported, and the channel list is 1 octet, with bits 1 to 7 set to zero. If the first bit field is set to zero (i.e., not all channels in that band are supported), then the subsequent bit fields indicate which individual channels are supported. The bit field corresponding to a channel number shall be set to one to indicate that the channel is supported and set to zero to indicate the channel is not supported. Bit maps are allocated on octet boundaries; unused bits are reserved. When multiple bands are supported, as indicated in the Supported Bands field, the corresponding channel lists are concatenated in order, such that the channel lists occur in the order of the bands given in Table 10-48, i.e., the channel list corresponding to the band indicated by bit 0 of the Supported Bands field is first if bit 0 is set to one. The term *channel* here refers to a WPAN channel, as defined in 11.1.3.9. The mapping between a TVWS channel and a PHY channel is not within the scope of this standard.

0	1	2	...	n
All channels supported	Channel 1 supported	Channel 2 supported	...	Channel n supported

Figure 10-89—Channel List field format

10.7.3.3 TVWS Device Category IE

The TVWS Device Category IE Content field shall be formatted as in Figure 10-90.

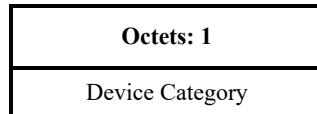


Figure 10-90—TVWS Device Category IE Content field format

Valid values of the Device Category field are given in Table 10-52.

Table 10-52—Device Category field values

Value	Description
0	Stationary and independent device
1	Stationary and dependent device
2	Non-stationary and independent device
3	Non-stationary and dependent device
4–255	Reserved

10.7.3.4 TVWS Device Identification IE

The TVWS Device Identification IE Content field shall be formatted as shown Figure 10-91.

Octets: 1	variable
ID Type	Device ID

Figure 10-91—TVWS Device Identification IE Content field format

Valid values of the ID Type field are given in Table 10-53.

Table 10-53—ID Type field values

Value	Description
0	US specific regulator assigned ID
1	UK specific regulator assigned ID
2	Canada specific regulator assigned ID
3	Japan specific regulator assigned ID
4	Korea specific regulator assigned ID
5	EU specific regulator assigned ID
6	Manufacturer serial number
7	Vendor specific
8–255	Reserved

For an ID Type field indicated as regulator assigned, the Device ID field shall be formatted as shown in Figure 10-92. For other non-reserved values in Table 10-53, the Device ID field contains only the ID String field.

Octets: 1	variable
Device Category	ID String

Figure 10-92—Device ID field format

The Device Category field is defined in 10.7.3.3.

The ID String field shall be formatted as shown in Figure 10-93.

Octets: 1	variable
Length	ID Value

Figure 10-93—ID String field format

The Length field specifies the number of octets that follows in the ID Value field.

The encoding of characters into the ID Value field is defined by regulators or can be vendor specific and is outside the scope of this standard.

10.7.3.5 TVWS Device Location IE

The TVWS Device Location IE Content field shall be formatted as shown Figure 10-94.

Octets: 1	17	17	...	17
Number of Locations	Device Location 1	Device Location 2	...	Device Location n

Figure 10-94—TVWS Device Location IE Content field format

The Number of Locations field indicates the number of Device Location fields in the IE.

The Device Location field shall be formatted as shown in Figure 10-95.

Octets: 1	16
Location ID	Device Location Element

Figure 10-95—Device Location field format

The Location ID field provides an ID of a particular location for which a device is requesting channel list info. This field is used as part of the channel list response to allocate available channel info to a particular location ID.

The Device Location Element field shall be encoded as described in IETF RFC 6225, section 2.1. The first two fields, Option Code and OptLen, are omitted for the Device Location Element field.

10.7.3.6 TVWS Channel Information Query IE

The TVWS Channel Information Query IE Content field shall be formatted as shown in Figure 10-96.

Octets: 1	1	0/variable
Channel List ID	Channel Info Status	Channel List Info

Figure 10-96—TVWS Channel Information Query IE Content field format

The Channel List ID field is incremented when the channel data is updated. When the Channel Info Status field indicates that this is a channel data request, the Channel List ID field is set to the ID value provided when channel data was last received. If channel data has not been received the Channel List ID field is set to zero in the request.

The Channel Info Status field shall be formatted as shown in Figure 10-97.

Bits: 0	1–3	4–7
Channel List Request/Response	Number of Locations	Reserved

Figure 10-97—Channel Info Status Content field format

The Channel List Request/Response field shall be set to zero if this is a request for information and shall be set to one if it is a response to a request. When the Channel Info Status field indicates a request, TVWS Device Identification IEs and a TVWS Device Location IE may be included in the request frame.

When the Channel List Request/Response field is set to indicate a response, the Number of Locations field indicates the number of locations for which the channel info is available. Otherwise, the Number of Locations field is reserved.

The Channel List Info field shall be present when Channel List Request/Response is set to indicate a response.

Each entry in the Channel List Info field contains the specific information on available channels as shown in Figure 10-98.

Octets: 1	1	0/1	0/variable
Location ID	Channel List Status	Number of TVWS Channels	Available Channel

Figure 10-98—Channel List Info field format

The Channel List Status field shall be present when Channel list Request/Response is set to indicate a response. Valid values of the Channel List Status field are given in Table 10-54.

Table 10-54—Channel List Status field values

Status	Description
0	Available channel list verified for a device location
1	Request not successful due to device ID not being verified
2	Request not successful due to device location being out of the geographic coordinate
3	Request not successful due to one or more parameters having invalid values
4–255	Reserved

When the Channel Info Status field indicates that this is a response with available channel list for verified device locations, the Number of TVWS Channels field and Available Channel field are included in the IE. For other status values these fields are not present.

The Available Channel field shall be formatted as shown in Figure 10-99.

Octets: 5	1	2
Available Frequency Range	Maximum TX Power	Valid Time

Figure 10-99—Available Channel field format

The Available Frequency Range field shall be formatted as shown in Figure 10-100.

Octets: 3	2
Starting Frequency	Bandwidth

Figure 10-100—Available Frequency Range field format

The Starting Frequency field specifies the starting frequency, in units of 1 kHz, where the TVWS spectrum is available.

The Bandwidth field indicates the bandwidth, in units of 1 kHz, of the available TVWS spectrum.

The Maximum TX Power field contains the maximum allowed transmit effective isotropic radiated power (EIRP) authorized for the TVWS channel, encoded as a two's-complement number in 0.5 dBm increments, in the range of -64 dBm to 63.5 dBm.

The Valid Time field contains the time, in minutes from the time of transmission, that the channel availability data is expected to remain valid; a valid time of zero indicates that the channel is available until further notice (e.g., as might be used for contact verification).

10.7.3.7 TVWS Channel Information Source IE

The TVWS Channel Information Source IE Content field shall be formatted as shown in Figure 10-101.

Octets: 1	0/16	0/8	0/8
Source Info	Known Source Location	Known Source Address	Known Source Available Channel

Figure 10-101—TVWS Channel Information Source IE Content field format

The Source Info field shall be formatted as shown in Figure 10-102.

Bits: 0	1	2	3–7
Location Present	Address Present	Available Channel Present	Reserved

Figure 10-102—Source Info field format

The Location Present field shall be set to one if the Known Source Location field is present and shall be set to zero otherwise.

The Address Present field shall be set to one if the Known Source Address field is present and shall be set to zero otherwise.

The Available Channel Present field shall be set to one if the Known Source Available Channel field is present and shall be set to zero otherwise.

The Known Source Location field contains the location of the device acting as the source of channel availability data and shall be encoded as described in IETF RFC 6225, section 2.1. The first two fields, Option Code and OptLen, are omitted for the Known Source Location field.

The Known Source Address field contains the extended address of the known source device.

The Known Source Available Channel field contains the TVWS channel being used by the known source and shall be formatted as shown in Figure 10-99.

10.7.3.8 CTM IE

The CTM IE Content field shall be formatted as shown in Figure 10-103.

Octets: 1	15	...	15
CTM Control	Channel Timing Information 1	...	Channel Timing Information <i>n</i>

Figure 10-103—CTM IE Content field format

Valid values of the CTM Control field are given in Table 10-55.

Table 10-55—CTM Control field values

Value	Description
0	Request for channel timing information
1	Success with full channel timing information on the available channels
2	Success with subset of channel timing information on the available channels
3	Success with no channel timing changes from previous query
4	Request declined due to unspecified reason
5	Request declined because of no capability for providing channel timing information
6	Request declined, database access timeout
7–255	Reserved

The Channel Timing Information fields shall only be present when it is a response to a request and the CTM Control field value indicates that channel timing information is available. The Channel Timing Information field shall be formatted as shown Figure 10-104.

Octets: 5	8	2
Available Frequency Range	Channel Availability Starting Time	Valid Time

Figure 10-104—Channel Timing Information field format

The Available Frequency Range field is defined in Figure 10-100.

The Channel Availability Starting Time field indicates the starting time in Coordinated Universal Time (UTC) from when the channel indicated in the Channel Number field is available for operation. UTC is defined by CCIR Recommendation 460-4.

The Valid Time field indicates the duration of frequency availability as described in 10.7.3.6.

The information in Figure 10-104 may be aggregated to show multiple durations of the channel time scheduling.

10.7.3.9 Timestamp IE

The Timestamp IE Content field shall be formatted as shown in Figure 10-105.

Octets: 4
Transmit Timestamp

Figure 10-105—Timestamp IE Content field format

The Transmit Timestamp field shall be set to the time, in units of 10 picoseconds, of the transmitter time reference at the antenna, when the packet containing this IE is transmitted. The timing reference is the RMARKER of the frame, as defined in 10.29.1.

10.7.3.10 Timestamp Difference IE

The Timestamp Difference IE Content field shall be formatted as illustrated in Figure 10-106.

Octets: 4
RX TX Time Difference

Figure 10-106—Timestamp Difference IE Content field format

The RX TX Time Difference field contains the difference in time, in units of 10 picoseconds, from the time the most recent RFRAME was received to the time the frame containing the IE is transmitted. The reference for these time values is the RMARKER.

10.7.4 MAC constants and PIB attributes for TVWS

TVWS attributes are described in Table 10-56.

Table 10-56—TVWS related PIB attributes

Attribute	Type	Range	Description	Default
<i>macStartBandEdge</i>	Integer	0–16 777 215	Frequency in kilohertz indicating the lower edge of the band.	608 000
<i>macEndBandEdge</i>	Integer	0–16 777 215	Frequency in kilohertz indicating the upper edge of the band.	614 000

10.8 TVWS multichannel cluster tree PAN (TMCTP)

10.8.1 Overview of TMCTP

The simplest form of a cluster tree network is a single cluster network, but larger networks are possible by forming a mesh of multiple neighboring clusters. Once predetermined application or network requirements are met, the first PAN coordinator instructs a device to become the PAN coordinator of a new cluster adjacent to the first one. Other devices gradually connect and form a multicluster network structure, such as the one seen in Figure 10-107. The lines in Figure 10-107 represent the parent-child relationships of the devices and not the communication flow. The advantage of a multicluster structure is increased coverage area, while the disadvantage is an increase in message latency.

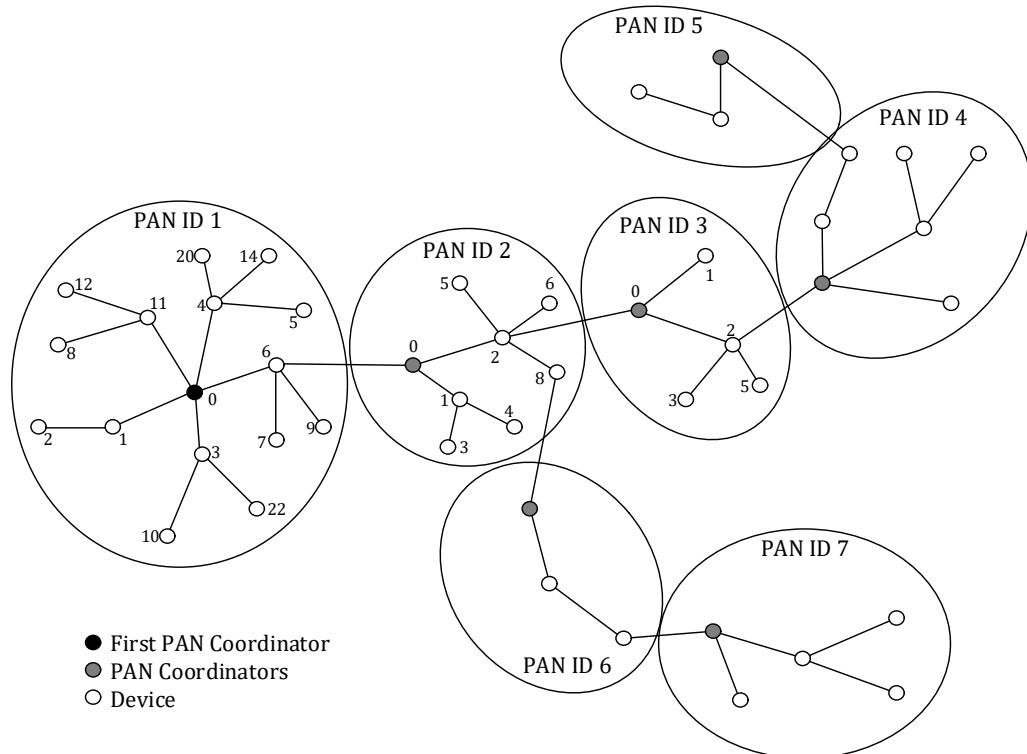


Figure 10-107—Cluster tree network

A TMCTP is a form of cluster tree network where the super PAN coordinator (SPC) is the overall PAN coordinator that provides synchronization services to other PAN coordinators in the cluster. The SPC also has access to the GDB server to provide TVWS channel availability information to other PAN coordinators. An example is shown in Figure 10-108. In the TMCTP, collisions between clusters can be reduced because each cluster uses its own channel; in addition, the coverage area is increased through the TMCTP parent-child structure. Each TMCTP-parent PAN coordinator, including the SPC, communicates with its TMCTP-child PAN coordinators during the CAP or CFP of the TMCTP-parent PAN coordinator superframe. Each one also receives beacon frames of its TMCTP-child PAN coordinators on a dedicated channel during the DBS assigned to them in the BOP, as shown with an asterisk (*) in Figure 10-108.

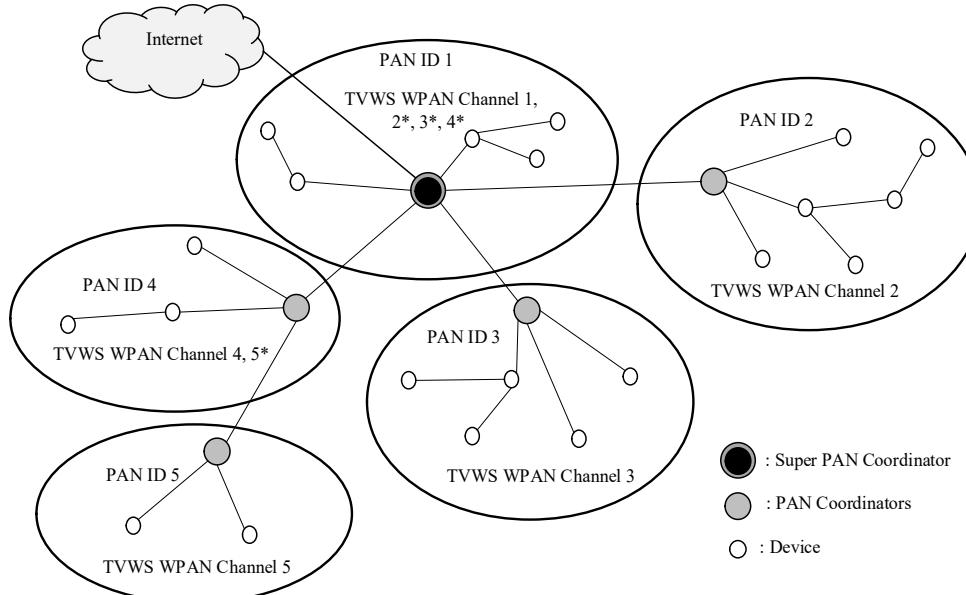


Figure 10-108—Example of TVWS multichannel cluster tree PAN

TVWS allows the optional use of a superframe structure in a TMCTP that is extended by the addition of a BOP to the active portion of the superframe. The format of the TMCTP superframe is defined by the SPC which sends an enhanced beacon containing a TMCTP Specification IE, as in 10.8.4.1. The TMCTP superframe is bounded by beacons sent by the SPC. The active portion of the TMCTP superframe is composed of a beacon, a CAP, a CFP, and a BOP. An example of a TMCTP superframe including a BOP is illustrated in Figure 10-109. The BOP is composed of one or more DBSs. A DBS is used to communicate beacons between a TMCTP-parent PAN coordinator and one of its TMCTP-child PAN coordinator(s).

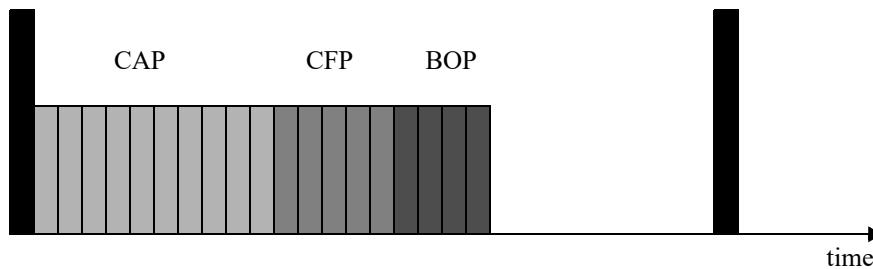


Figure 10-109—TMCTP superframe extension

10.8.2 Superframe use for TMCTP operation

The TMCTP superframe is an extension of the basic superframe defined in 10.2. The active portion of the TMCTP superframe is composed of four parts, which is illustrated in Figure 10-109.

- The Beacon frame, as described in 7.3.1, which is used to set the timing allocations and to communicate management information for the PAN.
- The CAP, as described in 10.2.2.2, which is used to communicate commands and/or data.
- The CFP, as described in 10.2.2.3, which is composed of GTSs. No transmissions within the CFP shall use a CSMA-CA mechanism to access the channel.
- The BOP, as described in 10.2.2.4, which is composed of one or more DBSs. A DBS is used to communicate beacons between a TMCTP-parent PAN coordinator (including the SPC) and one of its TMCTP-child PAN coordinator(s) in a TMCTP.

The *SD* and *BI* of the TMCTP superframe are the same as described in 10.2. The MAC PIB attribute *macTmctpExtendedOrder* describes the extended length of the active portion of the superframe. The value of *macTmctpExtendedOrder* and the extended duration, *ED*, are related as follows:

$$\begin{aligned} ED &= aBaseSuperframeDuration \times 2^{macTmctpExtendedOrder} \\ &= aBaseSlotDuration \times aNumSuperframeSlots \times 2^{macTmctpExtendedOrder} \end{aligned}$$

for

$$0 \leq macTmctpExtendedOrder \leq (macBeaconOrder - macSuperframeOrder) \leq macBeaconOrder \leq 14$$

The ED of each TMCTP superframe shall be divided into $aNumSuperframeSlots \times 2^{macTmctpExtendedOrder}$ equally spaced slots of duration *aBaseSlotDuration* in a BOP. The BOP consists of multiple DBSs. Each DBS is composed of one or more base slots, which are *aBaseSlotDuration* in length.

The total duration of the active portion of each TMCTP superframe consists of the *SD* and the *ED*.

An example of a TMCTP superframe structure is shown in Figure 10-110, according to various values of the *macBeaconOrder* (*BO*), the *macSuperframeOrder* (*SO*), and the *macTmctpExtendedOrder* (*EO*).

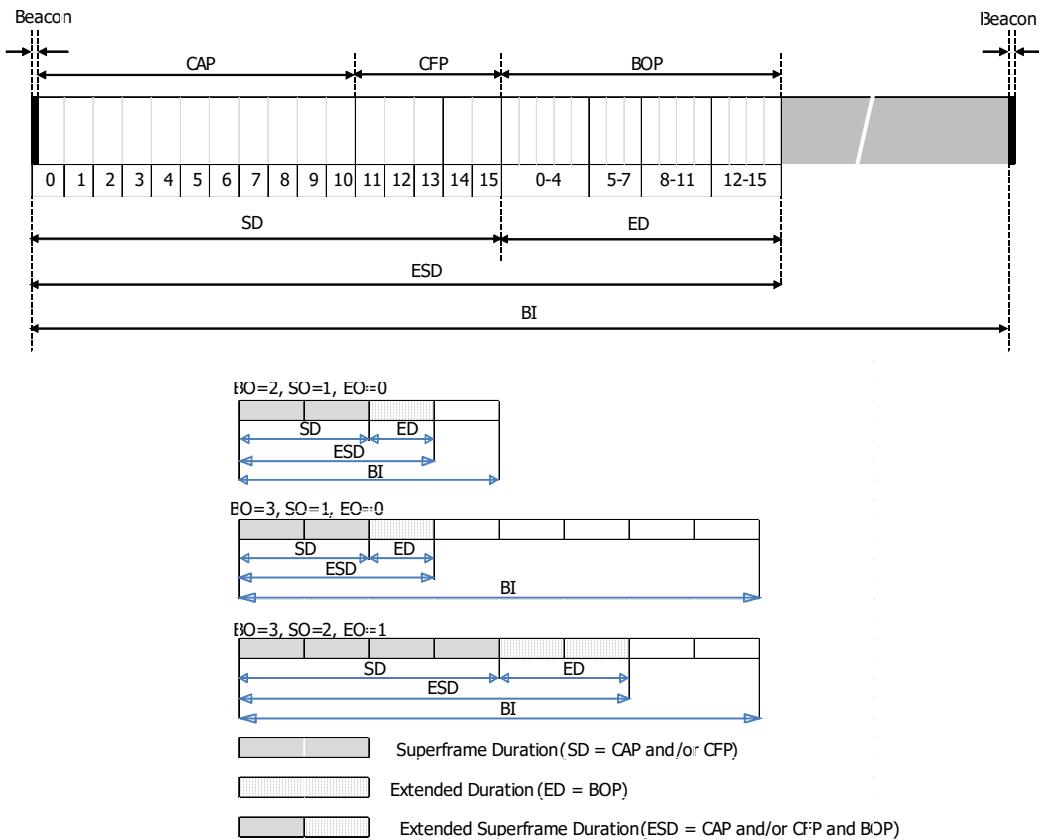


Figure 10-110—An example of the TMCTP superframe structure

10.8.3 Starting and maintaining TMCTPs

Figure 10-111 shows an example with a suggested message sequence for TMCTP formation between the SPC, which is the TMCTP-parent PAN coordinator, and a TMCTP-child PAN coordinator.

In step A, the SPC obtains the set of available TVWS channels from the GDB through the Internet. The protocol used to access the GDB over the Internet is outside the scope of this standard. Alternatively, the SPC may obtain the set of available TVWS channels from another device. The SPC maps the TVWS channels to corresponding PHY channels, selects one of the available PHY channels, and transmits its Beacon frame in that channel. The TMCTP-child PAN coordinator completes the scan procedure over all PHY channels.

In Step B, the SPC transmits an Enhanced Beacon frame containing a TMCTP Specification IE, as described in 10.8.4.1. The TMCTP Specification IE shall be included in all Enhanced Beacon frames that are sent in a TMCTP-enabled PAN. Upon successful reception of the Enhanced Beacon frame from the SPC, the TMCTP-child PAN coordinator may request a DBS allocation or a DBS deallocation by sending a DBS Request command, as described in 10.8.5.1, to the SPC. Upon receiving the DBS Request command, the SPC will allocate or deallocate a DBS slot and a channel and generate a DBS Response command, as described in 10.8.5.2, to report the slot and the channel allocated or deallocated. The SPC may generate the DBS Response command for the deallocation without the request of the TMCTP-child PAN coordinator.

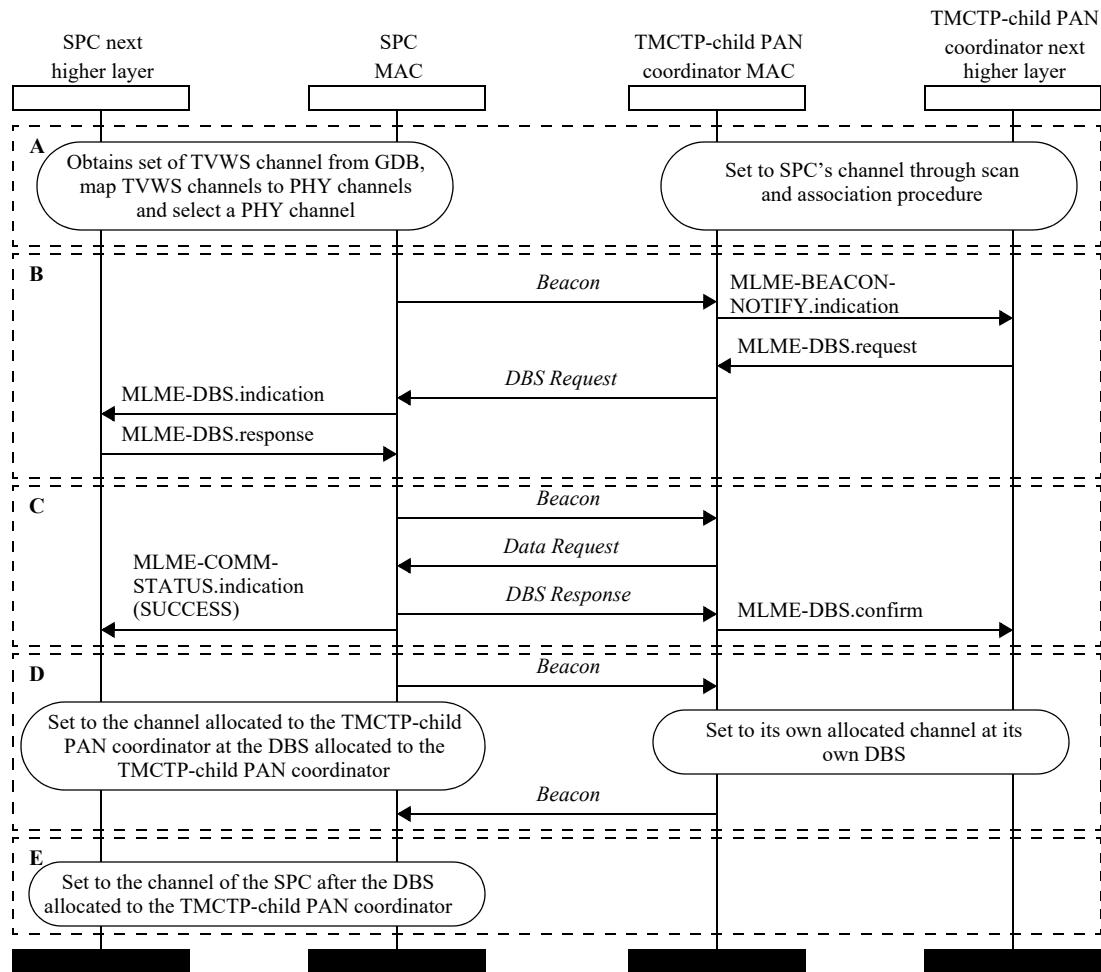


Figure 10-111—Example message sequence chart between SPC and TMCTP-child PAN coordinator

In Step C, the SPC indicates pending data for the TMCTP-child PAN coordinator in its Beacon frame. The TMCTP-child PAN coordinator sends the Data Request command. Upon receiving the Data Request command, the SPC replies with the DBS Response command generated in Step B. The SPC then sends its own Beacon frame.

In Step D, the SPC switches to the channel allocated to the TMCTP-child PAN coordinator and listens for the Beacon frame from the TMCTP-child PAN coordinator. If the SPC does not receive a Beacon frame from the TMCTP-child PAN coordinator within three BI s, the SPC switches to the SPC channel and sends a DBS Response command to the TMCTP-child PAN coordinator in next superframe of the SPC.

In Step E, upon receiving the Beacon frame during the slot allocated to the TMCTP-child PAN coordinator on the channel allocated to the TMCTP-child PAN coordinator, the SPC switches to its own dedicated channel.

During the CAP of the SPC TMCTP superframe, each TMCTP-child PAN coordinator sends a DBS Request command to the SPC and receives a DBS Response command from the SPC. The SPC switches to the channel allocated to the TMCTP-child PAN coordinator before the DBS slot time allocated to the

TMCTP-child PAN coordinator. Each TMCTP-child PAN coordinator forms an independent PAN by transmitting its beacon during the allocated DBS slot.

Figure 10-112 provides another example for TMCTP formation between two PAN coordinators, where one is the TMCTP-parent PAN coordinator and the other is a TMCTP-child PAN coordinator.

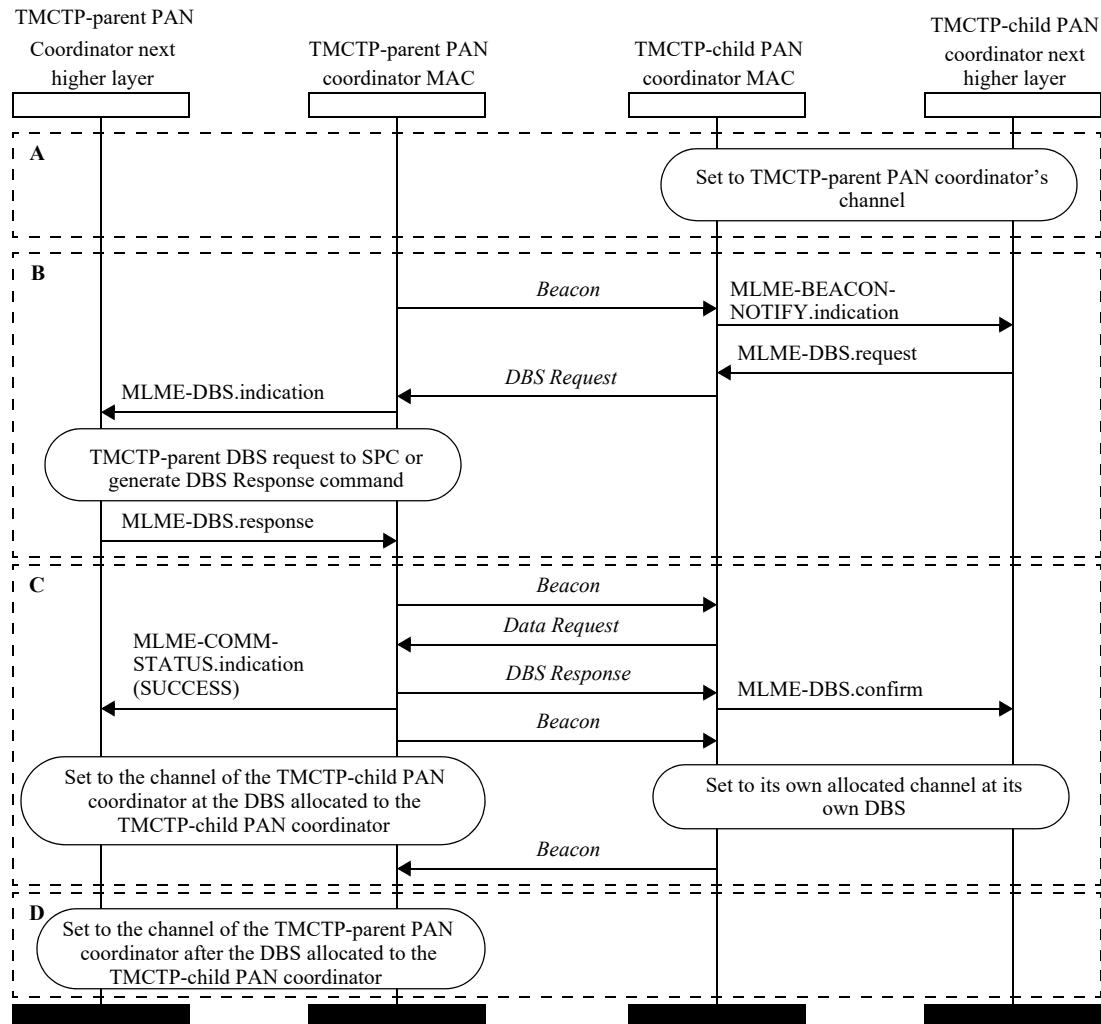


Figure 10-112—Example message sequence chart between TMCTP PAN coordinators

In Step A, the TMCTP-child PAN coordinator performs a scan procedure and waits for the Beacon frame of the TMCTP-parent PAN coordinator.

In Step B, the TMCTP-parent PAN coordinator sends an Enhanced Beacon frame containing a TMCTP Specification IE, as defined in 10.8.4.1. Upon successful reception of the Enhanced Beacon frame from the TMCTP-parent PAN coordinator, the TMCTP-child PAN coordinator requests a channel and a slot by using the DBS Request command sent to the TMCTP-parent PAN coordinator. Upon receiving the DBS Request command, the TMCTP-parent PAN coordinator either directly generates the DBS Response command reporting the slot and the channel allocated or deallocated, or sends the DBS Request command to the SPC and then receives the DBS Response command from the SPC. The TMCTP-parent PAN coordinator may generate the DBS Response command for the deallocation without a request of the TMCTP-child PAN coordinator.

In Step C, the TMCTP-parent PAN coordinator sends a Beacon frame. The TMCTP-parent PAN coordinator switches to the channel allocated to the TMCTP-child PAN coordinator and receives the Beacon frame from the TMCTP-child PAN coordinator.

In Step D, upon receiving the Beacon frame during the slot allocated to the TMCTP-child PAN coordinator on the channel allocated to the TMCTP-child PAN coordinator, the TMCTP-parent PAN coordinator switches to its own dedicated channel.

During CAP of the TMCTP-parent PAN coordinator, which has a relay capability or a channel allocation capability, each TMCTP-child PAN coordinator sends a DBS Request command to the TMCTP-parent PAN coordinator and receives the DBS Response command from the TMCTP-parent PAN coordinator. The TMCTP-parent PAN coordinator switches to the channel allocated to the TMCTP-child PAN coordinator during the DBS slot allocated to each TMCTP-child PAN coordinator. Each TMCTP-child PAN coordinator manages its own WPAN by transmitting a Beacon frame during the allocated DBS slot time.

Figure 10-113 shows an example of the multichannel allocation for the network topology as presented in Figure 10-108. In this case, the SPC operates on the dedicated channel, which is Channel 1 in Figure 10-113, and switches to the dedicated channels of TMCTP-child PAN coordinators 2, 3, and 4 during their DBSs. Similarly, TMCTP-child PAN coordinator 4 operates on the dedicated channel, which is Channel 4, and switches to the dedicated channel of TMCTP-child PAN coordinator 5 during its DBS to communicate with TMCTP-child PAN coordinator 5.

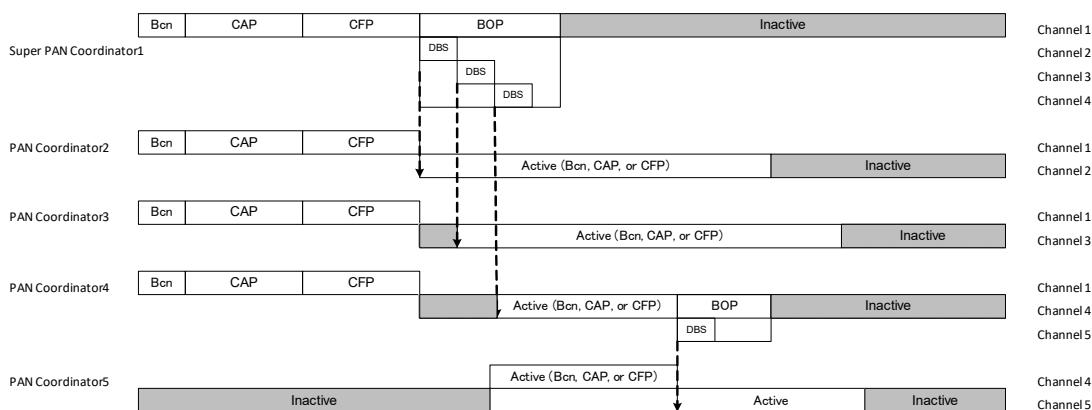


Figure 10-113—Example TMCTP BOP allocation

10.8.4 Nested IEs for TMCTP

10.8.4.1 TMCTP Specification IE

The TMCTP Specification IE Content field shall be formatted as illustrated in Figure 10-114.

Bits: 0–3	4	5	6	7	8–15	16–23	variable
BOP Order	TMCTP Frame Pending	DBS Allocation Capability	Channel Allocation Capability	Channel Allocation Relay Capability	Hop Count to SPC	Number of PAN IDs Pending	PAN ID List

Figure 10-114—TMCTP Specification IE Content field format

The BOP Order field contains the value *macTmctpExtendedOrder* as an unsigned integer.

The TMCTP Frame Pending field shall be set to one if the TMCTP-parent PAN coordinator has more frames for the TMCTP-child PAN coordinator. Otherwise, this field shall be set to zero.

The DBS Allocation Capability field shall be set to one if the device is capable of allocating a DBS to the TMCTP-child PAN coordinator; it shall be set to zero otherwise.

The Channel Allocation Capability field shall be set to one if the device is capable of allocating a dedicated channel to the TMCTP-child PAN coordinator; it shall be set to zero otherwise.

The Channel Allocation Relay Capability field shall be set to one if the device is capable of relaying a DBS request of the TMCTP-child PAN coordinator; it shall be set to zero otherwise.

The Hop Count to SPC field indicates the number of hops to reach the SPC.

The Number of PAN IDs Pending field indicates the number of PAN IDs contained in the PAN ID List field of the beacon frame.

The PAN ID List field contains the PAN IDs of the TMCTP-child PAN coordinators that currently have messages pending with the TMCTP-parent PAN coordinator.

10.8.5 MAC commands for TMCTP

10.8.5.1 DBS Request command

The Destination Addressing Mode field and Source Addressing Mode field shall be set to indicate short addressing.

The Frame Pending field shall be set to zero. The AR field shall be set to one. the Frame Version field shall be set to two.

The Destination PAN ID field shall contain the PAN ID of the SPC, and the Destination Address field shall contain the address of the SPC. The Source PAN ID field shall contain the value of *macPanId*. The network management entity should assure that each PAN coordinator has a unique PAN ID. The Source Address field shall contain the value of *macShortAddress*.

The DBS Request command Content field shall be formatted as shown in Figure 10-115.

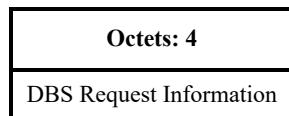


Figure 10-115—DBS Request command Content field format

The DBS Request Information field shall be encoded as shown in Figure 10-116.

Bits: 0:15	16:19	20:22	23	24:31
Requester Short Address	DBS Length	Reserved	Characteristics Type	Number of the Descendant

Figure 10-116—DBS Request Information field format

The Requester Short Address field shall be set to the short address of the coordinator requesting a DBS.

The DBS Length field shall contain the number of *aBaseSlotDuration* being requested for a DBS.

The Characteristics Type field shall be set to one if the characteristics refer to a DBS allocation or zero if the characteristics refer to a DBS deallocation.

The Number of the Descendant field indicates the actual or expected number of TMCTP-child PAN coordinators. It may be set to zero if the PAN coordinator is not clear about how many descendants it will have.

10.8.5.2 DBS Response command

The Destination Addressing Mode field and Source Addressing Mode field shall be set to indicate short addressing.

The Frame Pending field, the AR field, and the Frame Version field shall be set to zero, one, and two, respectively.

The Destination PAN ID field shall contain the source PAN ID from the DBS request frame, and the Destination Address field shall contain the source address from the DBS request frame. The Source PAN ID field shall contain the value of *macPanId*, and the Source Address field shall contain the value of *macShortAddress*.

The DBS Response command Content field shall be formatted as shown in Figure 10-117.

Octets: 10
DBS Response Information

Figure 10-117—DBS Response command Content field format

The DBS Response Information field shall be encoded as shown in Figure 10-118.

Octets: 2	1	1	1	3	1	1
Requester Short Address	Allocated DBS Starting Slot	Allocated DBS Length	Allocated PHY Channel Number	Start Band Edge	Starting PHY Channel ID	Ending PHY Channel ID

Figure 10-118—DBS Response Information field format

The Requester Short Address field shall be set to the short address of the coordinator requesting a DBS.

The Allocated DBS Starting Slot field shall contain the time of first slot of the allocated DBS in the BOP, in units of *aBaseSlotDuration*.

The Allocated DBS Length field shall contain the length of the allocated DBS. If the Allocated DBS Length field is equal to zero, it indicates that the DBS slot and the dedicated channel are deallocated.

The Allocated PHY Channel Number field shall contain the channel number that the coordinator intends to use for all future communications.

The Start Band Edge field is the frequency in kilohertz indicating the lower edge of band that the coordinator will use for all future communications.

The Starting PHY Channel ID field shall contain the lowest channel number that is assigned by the TMCTP-parent PAN coordinator, including the SPC.

The Ending PHY Channel ID field shall contain the highest channel number that is assigned by the TMCTP-parent PAN coordinator, including the SPC.

10.8.6 MAC management service primitives for TMCTP

10.8.6.1 MLME-DBS.request

The MLME-DBS.request primitive is used when a TMCTP-child PAN coordinator requests the allocation or deallocation of a DBS and a channel to its TMCTP-parent PAN coordinator including the SPC.

The semantics of this primitive are as follows:

```
MLME-DBS.request (RequesterCoordAddr, RequestType, DbsLength, NumberOfDescendents, SecurityParams)
```

The primitive parameters are defined in Table 10-57.

Table 10-57—MLME-DBS.request parameters

Name	Type	Valid range	Description
RequesterCoordAddr	Short address	0x0000–0xffff	The address of the source requester PAN coordinator.
RequestType	Enumeration	ALLOCATION, DEALLOCATION	Indicates if the request is for allocation or deallocation of a TMCTP DBS.
DbsLength	Integer	0x00–0xff	Number of BOP slots being requested for the DBS.
NumberOfDescendents	Integer	0x00–0xff	The actual or expected number of descendant PAN coordinators. Set as zero if the PAN coordinator is not clear about how many descendants it will have.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

On receipt of an MLME-DBS.request primitive, the MLME generates a DBS request command, as described in 10.8.5.1.

The SecurityParams parameter specifies the level of security to be applied to the DBS request command. Typically, the DBS request command should not be implemented using security. However, if the TMCTP-child PAN coordinator requesting DBS allocation shares a key with the TMCTP-parent PAN coordinator, then security may be specified.

10.8.6.2 MLME-DBS.indication

The MLME-DBS.indication primitive is generated to indicate the reception of a DBS Request command.

The semantics of this primitive are as follows:

```
MLME-DBS.indication ( 
    CoordAddress,
    RequesterCoordAddr,
    RequestType,
    DbsLength,
    NumberOfDescendents,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-58.

Table 10-58—MLME-DBS.indication parameters

Name	Type	Valid range	Description
CoordAddress	Short address	0x0000–0xffff	The address of the coordinator that sent the DBS Request command.
RequesterCoordAddr	Short address	0x0000–0xffff	The address of the source requester PAN coordinator.
RequestType	Enumeration	ALLOCATION, DEALLOCATION	Indicates if the received request is for an allocation or deallocation of TMCTP DBS.
DbsLength	Integer	0x00–0xff	The value of the DBS Length field of the received DBS Request command.
NumberOfDescendents	Integer	0x00–0xff	The number of TMCTP-child PAN coordinators. Set as zero if the PAN coordinator is not clear about how many descendants it will have.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

Upon receipt of this primitive, the next higher layer of a TMCTP-parent PAN coordinator is notified of a request for a DBS allocation or deallocation.

10.8.6.3 MLME-DBS.response

The MLME-DBS.response primitive is used to initiate a response to an MLME-DBS.indication primitive.

The semantics of this primitive are as follows:

```
MLME-DBS.response      (
    CoordAddress,
    RequesterCoordAddr,
    DbsStartingSlot,
    DbsLength,
    ChannelNumber,
    StartBandEdge,
    StartingChNum,
    EndingChNum,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-59.

Table 10-59—MLME-DBS.response parameters

Name	Type	Valid range	Description
CoordAddress	Short address	0x0000–0xffff	The address of the Coordinator that sent DBS Request command.
RequesterCoordA ddr	Short address	0x0000–0xffff	The address of the source requester PAN coordinator.
DbsStartingSlot	Integer	0x0000–0xffff	The first slot of the allocated DBS in the BOP.
DbsLength	Integer	0x00–0xff	The size, in BOP slots, of the allocated DBS.
ChannelNumber	PHY Channel ID	As defined in Table 10-48	The channel number that the coordinator intends to use for all future communications.
StartBandEdge	Set of octets	As defined in 10.8.5.2	The frequency in kilohertz indicating the lower edge of the band, as defined in 10.8.5.2.
StartingChNum	PHY Channel ID	As defined in Table 10-48	The lowest channel number that is assigned by the TMCTP-parent PAN coordinator.
EndingChNum	PHY Channel ID	As defined in Table 10-48	The highest channel number that is assigned by the TMCTP-parent PAN coordinator.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

When the MLME of a TMCTP-parent PAN coordinator receives an MLME-DBS.response primitive, it generates a DBS response command, as described in 10.8.5.2, and attempts to send it to the TMCTP-child PAN coordinator requesting the allocation of a DBS and a channel.

10.8.6.4 MLME-DBS.confirm

The MLME-DBS.confirm primitive is used to inform the next higher layer of the initiating device of the result of its request for the allocation of a DBS and a channel.

The semantics of this primitive are as follows:

```
MLME-DBS.confirm      (
    RequesterCoordAddr,
    DbsStartingSlot,
    DbsLength,
    ChannelNumber,
    StartBandEdge,
    StartingChNum,
    EndingChNum,
    Status
)
```

The primitive parameters are defined in Table 10-60.

Table 10-60—MLME-DBS.confirm parameters

Name	Type	Valid range	Description
Requester CoordAddr	Short address	0x0000–0xffff	The address of the source requester PAN coordinator.
DbsStarting Slot	Integer	0x0000–0xffff	The first slot of the allocated DBS in the BOP.
DbsLength	Integer	0x00–0xff	Number of slots allocated for the DBS.
ChannelNumber	PHY Channel ID	As defined in Table 10-48	The channel number that the coordinator intends to use for all future communications.
StartBandEdge	Set of octets	As in defined in 10.8.5.2	The frequency in kilohertz indicating the lower edge of the band.
Starting ChNum	PHY Channel ID	As defined in Table 10-48	The lowest channel number that is assigned by the TMCTP-parent PAN coordinator.
EndingChNum	PHY Channel ID	As defined in Table 10-48	The highest channel number that is assigned by the TMCTP-parent PAN coordinator.
Status	Enumeration	SUCCESS, also see 8.2.2	The status of the attempt of the allocation of a DBS and a channel.

If the DBS allocation request was successful, then the status parameter will be set to SUCCESS. Otherwise, the status parameter will be set to indicate the type of failure.

10.8.7 MAC constants and PIB attributes for TMCTP

TMCTP attributes are described in Table 10-61.

Table 10-61—TMCTP related PIB attributes

Attribute	Type	Range	Description	Default
<i>macTmctpExtendedOrder</i>	Integer	0–14	The extended length of the active portion of the superframe, as defined in 10.8.2.	0

10.9 Multi-PHY management (MPM)

10.9.1 Overview of MPM

Multiple, different SUN PHYs can operate in the same location and within the same frequency band. In order to mitigate interference, an multi-PHY management (MPM) scheme is specified for SUNs to facilitate inter-PHY coexistence. For this purpose, the MPM scheme facilitates interoperability and negotiation among potential coordinators with different PHYs by permitting a potential coordinator to detect an operating network during its discovery phase using the common signaling mode (CSM) appropriate to the band being used. The MPM procedure can be used in conjunction with the CCA mechanism to provide coexistence.

10.9.2 Channel access: Enhanced Beacon frame timing for MPM procedure

In a PAN using superframe structure, a SUN device operating as a coordinator transmits an Enhanced Beacon frame containing a Coexistence Specification IE at fixed intervals, in addition to the usual periodic beacons. Figure 10-119 shows the Enhanced Beacon frame timing for PANs using superframe structure.

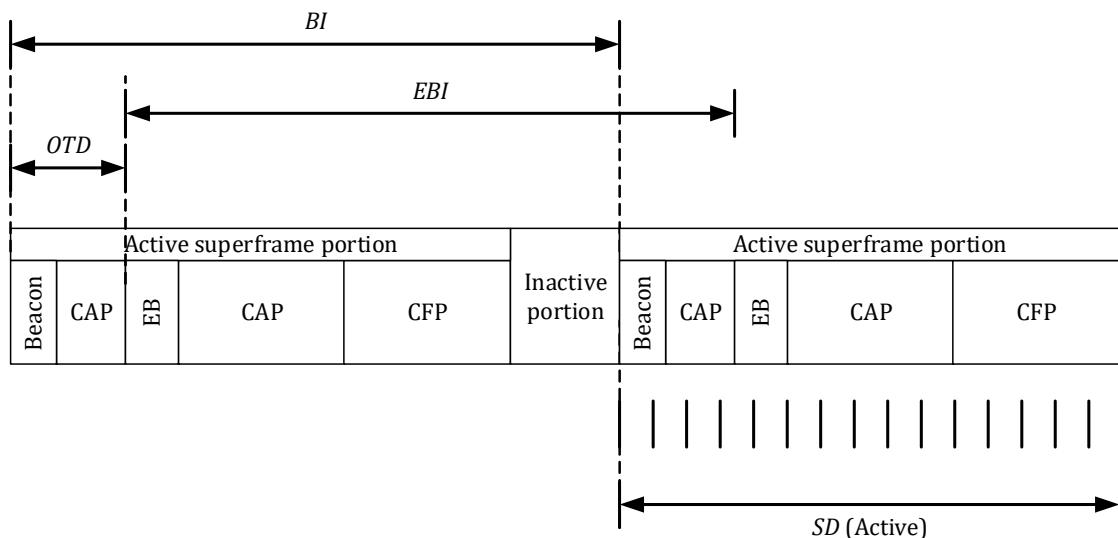


Figure 10-119—Timing information for Enhanced Beacon frames

The interval at which the coordinator shall start transmissions of its Enhanced Beacon frames is defined by *macEnhancedBeaconOrder*. The values of *macEnhancedBeaconOrder* and the enhanced beacon interval, *EBI*, are related as follows:

$$EBI = aBaseSuperframeDuration \times 2^{macEnhancedBeaconOrder}$$

The value of *macEnhancedBeaconOrder* should not be larger than the value of *macBeaconOrder*.

The time offset between the start of the periodic beacon transmission and the start of the following Enhanced Beacon frame transmission is described by *macOffsetTimeSlot*. The values of *macOffsetTimeSlot* and offset time duration, *OTD*, are related as follows:

$$OTD = aBaseSlotDuration \times macOffsetTimeSlot$$

In PANs not using superframe structure, the time offset between the starts of two Enhanced Beacon frames, EBI_{NBPAN} , is described by $macNbPanEnhancedBeaconOrder$. The resolution of time shall be $aBaseSlotDuration$. The values of $macNbPanEnhancedBeaconOrder$ and EBI_{NBPAN} are related as follows:

$$EBI_{NBPAN} = aBaseSlotDuration \times macNbPanEnhancedBeaconOrder$$

10.9.3 MPM procedure for inter-PHY coexistence

To facilitate interference avoidance among multiple SUNs utilizing different PHYs in the same location, all SUN coordinators operating at a duty cycle of more than 1% shall support the MPM procedures. In the MPM scheme, Enhanced Beacon frames are sent using the CSM, as defined in Table 11-31. Enhanced Beacon frames used in the MPM procedures described here are Enhanced Beacon frames containing a Coexistence Specification IE.

The transmission of Enhanced Beacon frames should take place in all the channels defined for CSM, as described in Table 11-31, that overlap with the channel(s) in operation. The scanning for Enhanced Beacon frames and the transmission of Enhanced Beacon Request commands should take place in all the channels defined for CSM that overlap with the channel of interest or at least two channels for PHY modes where the CSM requires frequency hopping.

In a PAN using superframe structure, an existing coordinator²² shall transmit an Enhanced Beacon frame at a fixed interval by using CSM. Any intending coordinator²³ shall first scan for an Enhanced Beacon frame until the expiration of the enhanced beacon interval or until an Enhanced Beacon frame is detected, whichever occurs first. If an intending coordinator detects an Enhanced Beacon frame, it shall either occupy another channel, achieve synchronization with the existing PAN, or stop communication. While specific mechanisms to achieve synchronization between two PANs utilizing different PHY modes are implementation dependent, the timing information applicable for synchronization purposes is specified in the Enhanced Beacon frame. Figure 10-120 illustrates the MPM procedure.

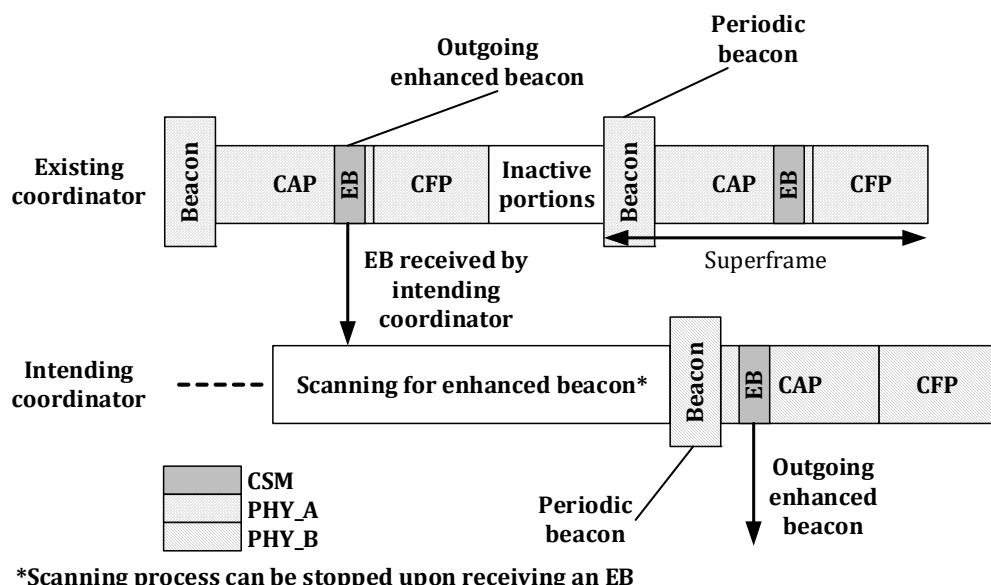


Figure 10-120—Inter-PHY mode coexistence in a PAN using superframe structure

²² An existing coordinator is a coordinator currently operating a network.

²³ An intending coordinator is a coordinator intending to start a separate network.

The Enhanced Beacon frame shall only be sent in the CAP.

In a PAN not using superframe structure, an existing coordinator should transmit an Enhanced Beacon frame periodically using the CSM. Any intending coordinator shall first scan for an Enhanced Beacon frame until the expiration of EBI_{NBPAN} or until an Enhanced Beacon frame is detected, whichever occurs first. The illustration of the procedure is given in Figure 10-121.

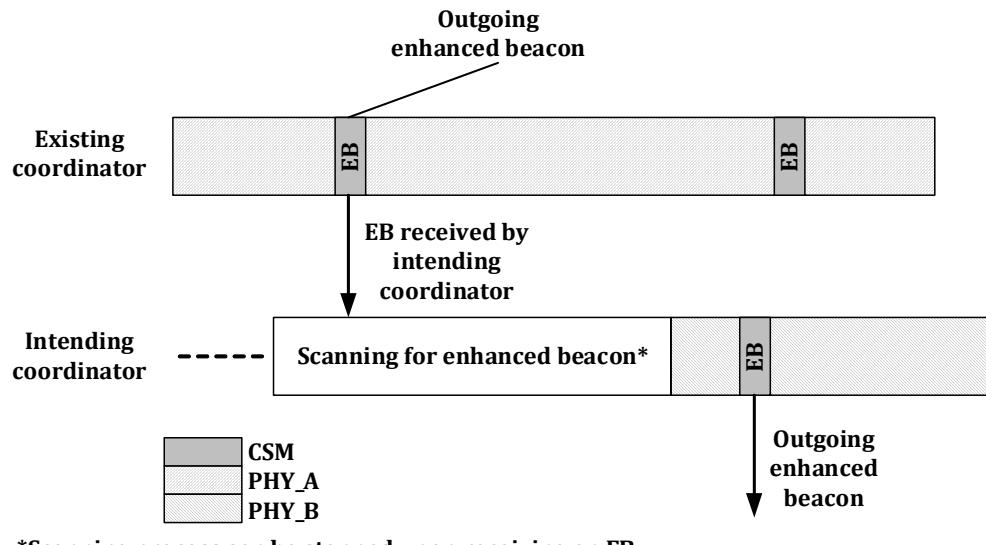


Figure 10-121—Inter-PHY mode coexistence in a PAN not using superframe structure

Alternatively, an Enhanced Beacon frame may be obtained in an on-demand manner. In this case, an Enhanced Beacon Request command containing the ID of the Coexistence Specification IE in the set of IE IDs is sent by the intending coordinator requesting an Enhanced Beacon frame from the existing coordinator. Upon receiving an Enhanced Beacon Request command, the existing coordinator (or any other device within the same area that is capable of receiving and transmitting an Enhanced Beacon Request command or Enhanced Beacon frame using the CSM) may respond by sending an Enhanced Beacon frame to the intending coordinator. The intending coordinator should transmit an Enhanced Beacon Request command at least once every EBI_{NBPAN} . To increase the probability of receiving an Enhanced Beacon Request command, the existing coordinator may periodically allocate a fraction of the CAP time to scan for the Enhanced Beacon Request command in CSM. The illustration of the procedure is given in Figure 10-122.

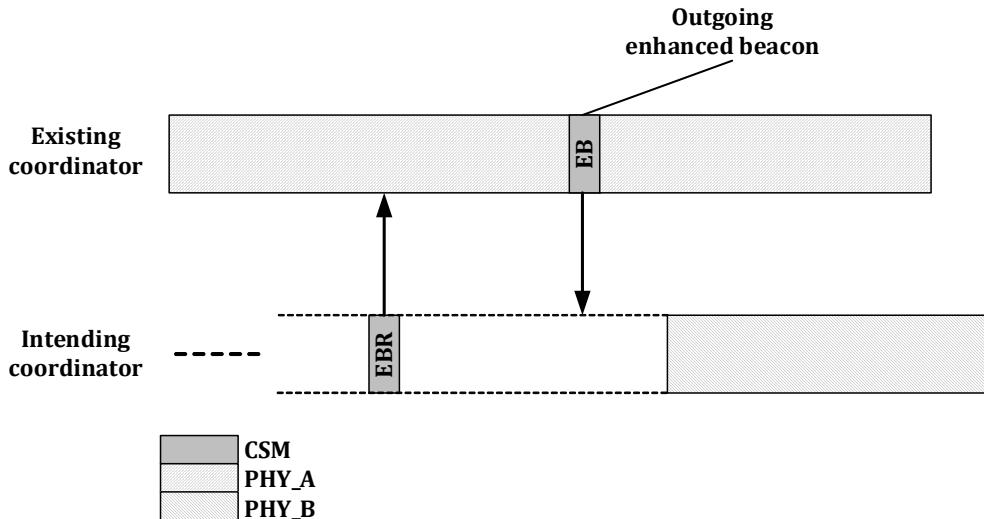


Figure 10-122—Alternative method for inter-PHY mode coexistence in a PAN not using superframe structure

10.9.4 Nested IEs for MPM

10.9.4.1 Coexistence Specification IE

The Coexistence Specification IE Content field shall be formatted as illustrated in Figure 10-123.

Bits: 0–3	4–7	8–11	12–15	16–19	20–23	24–39
Beacon Order	Superframe Order	Final CAP Slot	Enhanced Beacon Order	Offset Time Slot	CAP Backoff Offset	Enhanced Beacon Order

Figure 10-123—Coexistence Specification IE Content field format

The Beacon Order field, Superframe Order field, and Final CAP Slot field are as specified in 7.3.1.4. If the Beacon Order field is set to 15, the Superframe Order, Final CAP Slot, and Offset Time Slot fields shall be set to zero upon transmission and ignored upon reception.

The Enhanced Beacon Order field specifies the transmission interval of the Enhanced Beacon frames, as specified in 10.2.

The Offset Time Slot field specifies the time offset between the periodic beacon and the following Enhanced Beacon frame, as described in 10.2.

The CAP Backoff Offset field specifies the actual slot position in which the Enhanced Beacon frame is transmitted due to the backoff procedure in the CAP.

The Enhanced Beacon Order field specifies the transmission interval between consecutive Enhanced Beacon frames in the PAN not using superframe structure. The valid range for this field shall be 0–16383.

When generated in response to an Enhanced Beacon Request command that contained a set of requested IEs, the content of the Enhanced Beacon frame shall include the IEs corresponding to the requested IE IDs, as shown in Table 6-1.

10.9.5 MAC constants and PIB attributes for MPM

MPM attributes are described in Table 10-62.

Table 10-62—MPM related PIB attributes

Attribute	Type	Range	Description	Default
<i>macEnhancedBeaconOrder</i>	Integer	0–15	Specification of how often the coordinator transmits an Enhanced Beacon frame. If <i>macEnhancedBeaconOrder</i> = 15, no periodic Enhanced Beacon frame will be transmitted.	0
<i>macMpmIe</i>	Boolean	TRUE, FALSE	An indication of whether the Coexistence Specification IE, as defined in 10.9.4.1, is to be included in the Enhanced Beacon frame. If this value is TRUE, the Enhanced Beacon frame will include the Coexistence Specification IE. If this value is FALSE, the Enhanced Beacon frame will not include the Coexistence Specification IE.	FALSE
<i>macNbPanEnhancedBeaconOrder</i>	Integer	0–16383	Specification of how often the coordinator transmits an Enhanced Beacon frame in a PAN not using superframe structure (i.e., <i>macBeaconOrder</i> = 15). If <i>macNbPanEnhancedBeaconOrder</i> = 16383, no Enhanced Beacon frame will be transmitted.	16383
<i>macOffsetTimeSlot</i>	Integer	1–15	The offset between the start of the periodic beacon transmission and the start of the following Enhanced Beacon frame transmission expressed in superframe timeslots.	15

10.10 Priority channel access (PCA)

10.10.1 Overview of PCA

PCA allows priority channel access on the channel with critical event messages.

10.10.2 Channel access when using PCA

10.10.2.1 CSMA-CA with PCA

An MSDU or MSDU fragment in which the CriticalEventMessage parameter in the MCPS-DATA.request primitive is TRUE is referred to as a critical event message. The CSMA-CA with PCA backoff algorithm is used before the transmission of a critical event message during the CAP.

In a PAN using superframe structure when PCA is enabled (*macPriorityChannelAccess* is set to TRUE), the PCA Allocation IE shall be included in Enhanced Beacon frames that are sent at every beacon interval.

In a PAN using superframe structure, the MAC sublayer employs the slotted version of the CSMA-CA with PCA backoff algorithm for transmissions in the CAP of the superframe. Conversely, in a PAN not using superframe structure or if a beacon could not be located in a PAN using superframe structure, the MAC sublayer may transmit using the unslotted version of the CSMA-CA with PCA backoff algorithm.

CSMA-CA with PCA using a CCA Mode not equal to 4 is illustrated in Figure 10-124.

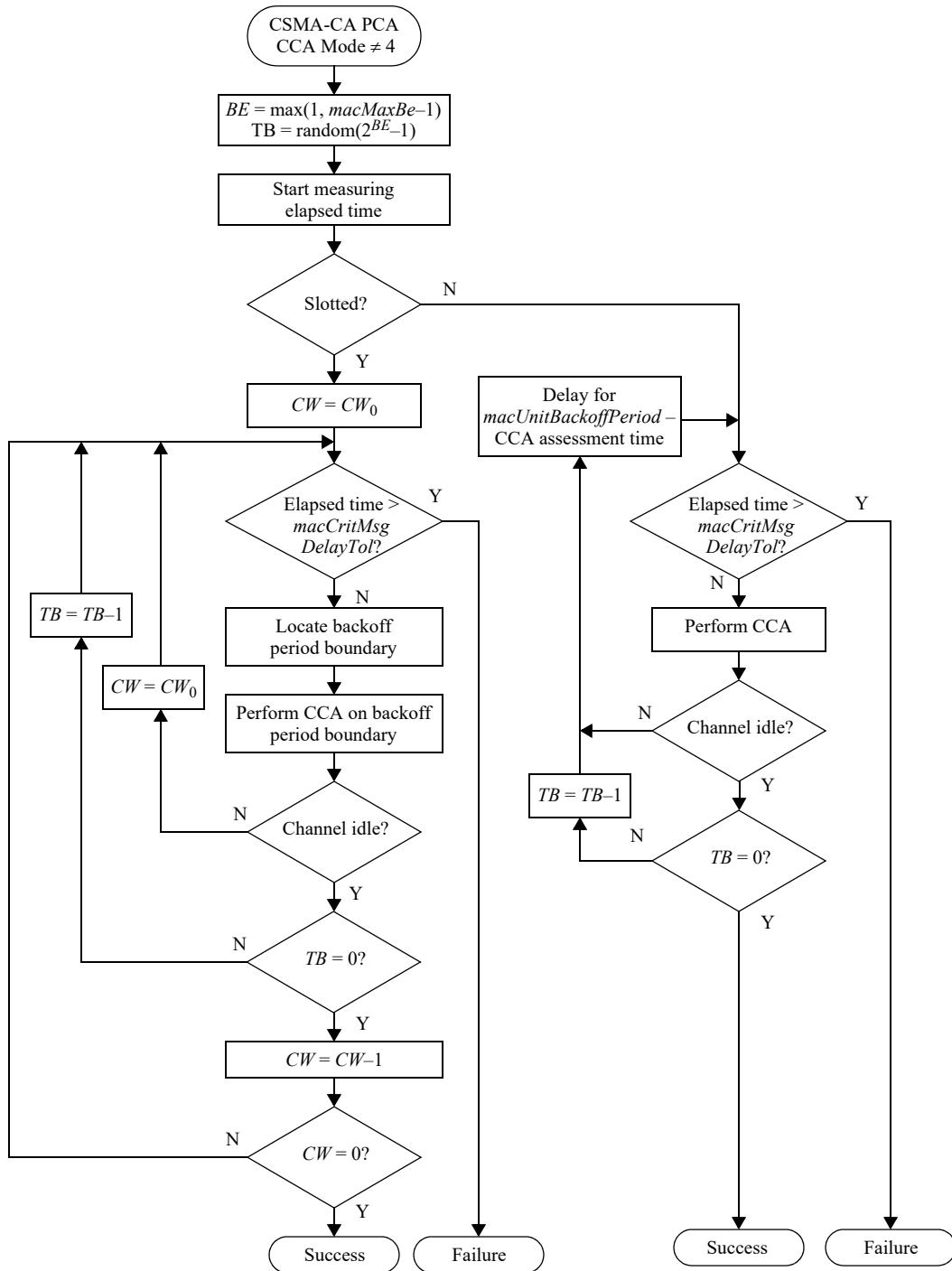


Figure 10-124—PCA CSMA-CA, non-Aloha

CSMA-CA with PCA using a CCA Mode equal to 4 is illustrated in Figure 10-125.

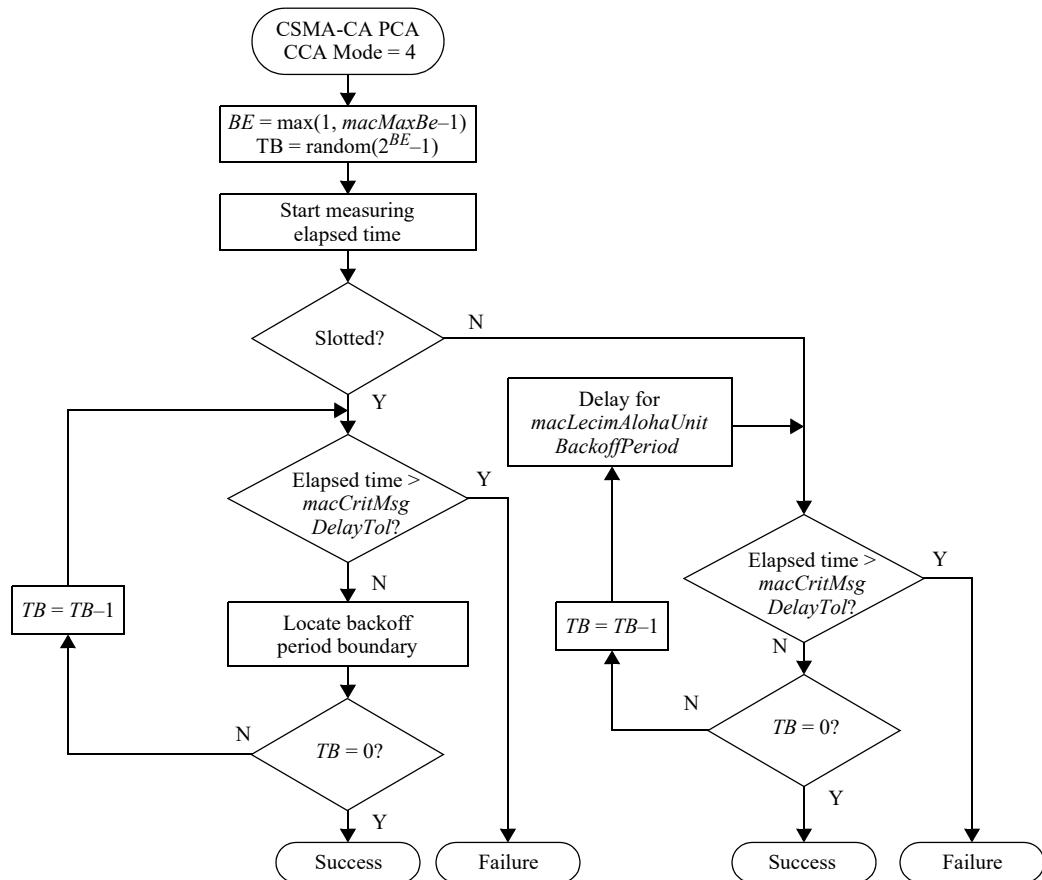


Figure 10-125—PCA CSMA-CA, Aloha

The variable NB is not used in the CSMA-CA with PCA backoff algorithm. The PCA backoff algorithm is used during the transmission of a priority message: the backoff exponent BE is initialized to the value of $(macMinBe - 1)$ or 1, whichever is larger, prior to the first transmission attempt, and BE remains constant for subsequent retransmissions. The MAC sublayer is responsible for maintaining a variable called TB , which indicates the number of remaining backoff periods since the start of the CSMA-CA with PCA backoff algorithm. TB is initialized to a random value between 0 and $(2^{BE} - 1)$. The PCA backoff algorithm follows a persistent CSMA mechanism, meaning that the device continues to monitor the channel and decrements TB by one any time the channel is sensed idle in a backoff period, in order to gain access to the channel in a timely manner.

In the slotted CSMA-CA with a PCA backoff algorithm, the MAC sublayer shall ensure that, after the persistent random backoff, the remaining CSMA-CA operations can be undertaken and the entire transaction can be transmitted before the end of the CAP. If TB is greater than the remaining number of backoff periods in the CAP, the MAC sublayer pauses the TB countdown at the end of the CAP and resumes it at the start of the CAP in the next superframe. If TB is less than or equal to the remaining number of backoff periods in the CAP, the MAC sublayer applies the PCA backoff algorithm one CCA attempt further and then again evaluates whether there is sufficient time to proceed. The MAC sublayer may proceed if the remaining CSMA-CA algorithm steps, the frame transmission, and any acknowledgment can be completed before the end of the CAP. If there is not sufficient time to proceed, the MAC sublayer waits until the start of the CAP in the next superframe before continuing to apply the PCA backoff algorithm.

When operating a LECIM PHY in a PAN not using superframe structure using unslotted CSMA-CA, the critical event message transmission may be initiated at any time.

In a PAN using superframe structure, the length of a PCA allocation shall be at least 880 symbol periods. When *macPriorityChannelAccess* is TRUE, the minimum number of PCA allocations in a superframe is defined by the MAC PIB attributes *macPcaAllocationSuperRate*, *macPcaAllocationRate*, and *macCritMsgDelayTol*. The relations of the parameters are illustrated in Table 10-63.

Table 10-63—PCA MAC PIB attribute relations

Value of <i>macPcaAllocationSuperRate</i>	<i>SD</i>	<i>macPcaAllocationRate</i>
FALSE	$SD \leq macCritMsgDelayTol/3$	Maximum value $\lfloor macCritMsgDelayTol/(3 \times SD) \rfloor$
TRUE	$macCritMsgDelayTol/3 < SD \leq macCritMsgDelayTol$	Minimum value 1
TRUE	$macCritMsgDelayTol < SD$	Minimum value $\lceil SD/macCritMsgDelayTol \rceil$

In Table 10-63, $\lfloor \cdot \rfloor$ indicates the closest integer less than or equal to its argument and $\lceil \cdot \rceil$ indicates the closest integer larger than or equal to its argument. When *macPcaAllocationSuperRate* is FALSE, *macPcaAllocationRate* is interpreted as a substrate, and it indicates the maximum number of consecutive superframes for which only one PCA allocation is required. In this case, the PCA allocations need only occur within the superframes having *macBsn* that are integer divisible by the *macPcaAllocationRate* value. When $SD \leq macCritMsgDelayTol/3$, *macPcaAllocationSuperRate* shall be set to FALSE; otherwise, it shall be set to TRUE. When *macPcaAllocationSuperRate* is TRUE, *macPcaAllocationRate* indicates the minimum number of PCA allocations required per superframe.

If there are multiple PCA allocations per superframe, the first allocation occurs at the start of the CAP. The remaining PCA allocations are distributed throughout the superframe, but no PCA allocation shall occur outside the CAP.

When a critical event message transmission is initiated within the CAP during a time that is not a PCA allocation, CSMA-CA, as defined in 6.3.2, with the previously described PCA backoff algorithm may be used.

If DSME is utilized with *macCapReduction* set to TRUE and the *MD* is longer than *macCritMsgDelayTol*, then *macPriorityChannelAccess* shall be set to FALSE.

When *macPriorityChannelAccess* is TRUE, a PCA allocation shall not occur if the CAP length duration is less than *aMinCapLength* plus the time required for a single PCA allocation.

10.10.2.2 LECIM ALOHA PCA

When PCA is in use with CCA Mode 4 (ALOHA), PCA is achieved using a modified version of the PCA backoff algorithm described in 10.10.2.1. Instead of one backoff period being equal to *macUnitBackoffPeriod*, a backoff period is defined as *macLecimAlohaUnitBackoffPeriod*.

When MPDU fragmentation is in use, the value of *macLecimAlohaUnitBackoffPeriod* should be long enough to accommodate the transmission of a single MPDU fragment with the associated IFS period and a

Frak frame. When MPDU fragmentation is not in use, the value of *macLecimAlohaUnitBackoffPeriod* should be long enough to accommodate the transmission of a maximum-sized MPDU with the associated IFS and an Ack frame.

When *macPriorityChannelAccess* is set as TRUE, each PCA allocation shall be at least four consecutive *macLecimAlohaUnitBackoffPeriod* in duration. The first PCA allocation shall begin at the start of the CAP. The number of PCA allocations per superframe is described by Table 10-63.

A PCA allocation cannot occur if the CAP length duration is less than *aMinCapLength* plus the time required for a single PCA.

10.10.3 Nested IEs for PCA

10.10.3.1 PCA Allocation IE

The PCA Allocation IE Content field shall be formatted as illustrated in Figure 10-126.

Bit: 0	1	2–15	16–23
PCA Used	Super-rate	Delay Tolerance	Allocation Rate

Figure 10-126—PCA Allocation IE Content field format

The PCA Used field is set according to the MAC PIB attribute *macPriorityChannelAccess*, with a value of zero indicating that *macPriorityChannelAccess* is FALSE and a value of one indicating that *macPriorityChannelAccess* is TRUE.

The Super-rate field is set according to the MAC PIB attribute *macPcaAllocationSuperRate* with a value of zero indicating that *macPcaAllocationSuperRate* is FALSE and a value of one indicating that *macPcaAllocationSuperRate* is TRUE.

The Delay Tolerance field describes the delay tolerance of a critical event message in units of 4 ms. The relation of *macCritMsgDelayTol* to the Delay Tolerance field value is as follows:

$$macCritMsgDelayTol = 4 \times \text{Delay Tolerance (ms)}$$

The Allocation Rate field is set according to the MAC PIB attribute *macPcaAllocationRate*, and in conjunction with *macPcaAllocationSuperRate*, it provides the rate at which PCA allocations are made, as described in 10.10.2.1.

10.10.4 MAC constants and PIB attributes for PCA

PCA attributes are described in Table 10-64.

Table 10-64—PCA related PIB attributes

Attribute	Type	Range	Description	Default
<i>macLecimAlohaUnitBack-offPeriod</i>	Integer	As defined in 10.10.2.2.	The number of symbols for backoff when PCA backoff algorithm is in use, as defined in 10.10.2.2.	—
<i>macLecimAlohaBe</i>	Integer	0– <i>macMinBe</i> .	The value of the constant backoff exponent for priority messages using CCA Mode 4 (ALOHA), as described in 10.10.2.2.	<i>macMinBe</i> –1
<i>macPriorityChannelAccess</i>	Boolean	TRUE, FALSE.	Indicates whether PCA is enabled. A value of TRUE indicates that it is enabled, while a value of FALSE indicates that it is disabled.	FALSE
<i>macPcaAllocationSuperRate</i>	Boolean	TRUE, FALSE.	Indicates the PCA allocation rate per superframe. A value of TRUE indicates one or more allocations per superframe. A value of FALSE indicates less than one allocation per superframe.	TRUE
<i>macPcaAllocationRate</i>	Integer	Minimum rate defined in 10.10.2.1; the maximum rate is 255.	The PCA allocation rate. If <i>macPcaAllocationSuperRate</i> is TRUE, the value is the number of allocations per superframe. If <i>macPcaAllocationSuperRate</i> is FALSE, the value is the number of superframes per PCA allocation.	1
<i>macCritMsgDelayTol</i>	Integer	0–65 532.	The maximum transaction delay, in milliseconds, for a critical event message before issuing an MCPS-DATA.confirm with Status set to TRANSACTION_EXPIRED, as defined in 10.10.3.1.	15 000

10.11 Slotted CSMA-CA algorithm

In slotted CSMA-CA, the backoff period boundaries of every device in the PAN shall be aligned with the superframe slot boundaries of the PAN coordinator; i.e., the start of the first backoff period of each device is aligned with the start of the beacon transmission. In slotted CSMA-CA, the MAC sublayer shall commence transmissions on the boundary of a backoff period. In unslotted CSMA-CA, the backoff periods of one device are not related in time to the backoff periods of any other device in the PAN.

Each device shall maintain three variables for each transmission attempt: *NB*, *CW*, and *BE*. *NB* and *BE* are described in 6.3.2.1. *CW* is the contention window length, defining the number of backoff periods that need to be clear of channel activity before the transmission can commence. The initial value of *CW*, *CW*₀, shall be two. The value of *CW* shall be initialized to *CW*₀ before each transmission attempt and reset to *CW*₀ each time the channel is assessed to be busy. If the received BLE field, as defined in Figure 7-7, is set to zero, *BE* shall be initialized to the value of *macMinBe*. If the received BLE field set to one, this value shall be initialized to the lesser of two and the value of *macMinBe*.

Figure 10-127 illustrates the steps of the slotted CSMA-CA algorithm. If the algorithm ends in “Success,” the MAC is allowed to begin transmission of the frame. Otherwise, the algorithm terminates with a channel access failure.

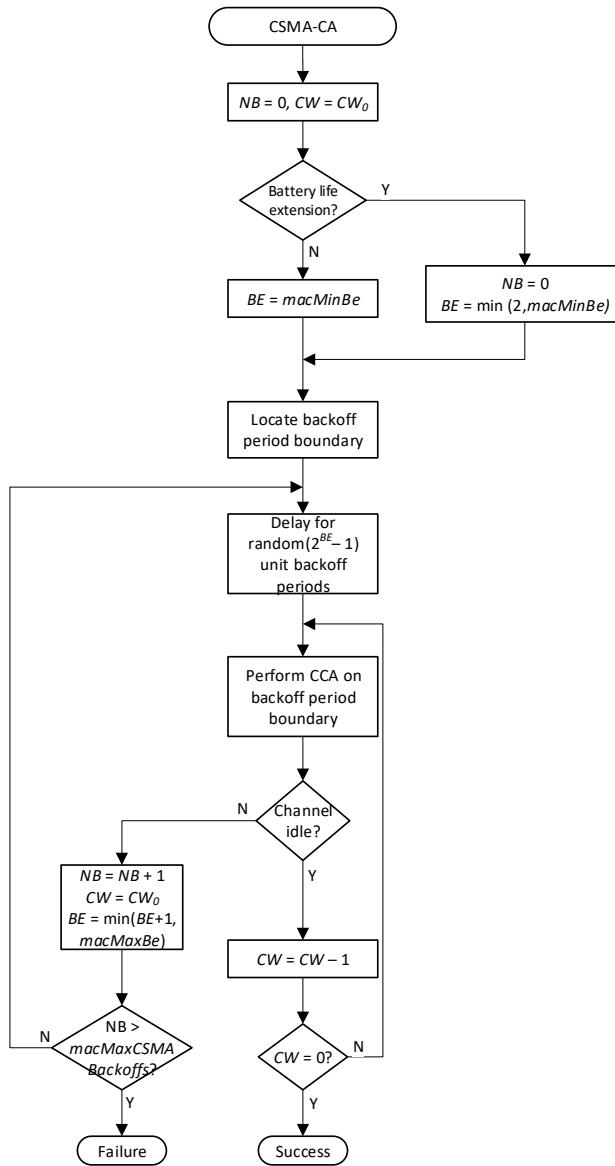


Figure 10-127—Slotted CSMA-CA algorithm

When the BLE field is set to zero, the MAC sublayer shall ensure that, after the random backoff, the remaining CSMA-CA operations can be undertaken, and the entire transaction can be transmitted before the end of the CAP. If the number of backoff periods is greater than the remaining number of backoff periods in the CAP, the MAC sublayer shall pause the backoff countdown at the end of the CAP and resume it at the start of the CAP in the next superframe. If the number of backoff periods is less than or equal to the remaining number of backoff periods in the CAP, the MAC sublayer shall apply its backoff delay and then evaluate whether it can proceed. The MAC sublayer shall proceed if the remaining CSMA-CA algorithm steps, the frame transmission, and any acknowledgment can be completed before the end of the CAP. If the MAC sublayer can proceed, it shall request that the PHY perform the CCA in the current superframe. If the MAC sublayer cannot proceed, it shall wait until the start of the CAP in the next superframe and apply a further random backoff delay before evaluating whether it can proceed again.

When the BLE field is set to one, the MAC sublayer shall ensure that, after the random backoff, the remaining CSMA-CA operations can be undertaken, and the entire transaction can be transmitted before the

end of the CAP. The backoff countdown shall only occur during the first *macBattLifeExtPeriods* full backoff periods after the end of the IFS period following the beacon. The MAC sublayer shall proceed if the remaining CSMA-CA algorithm steps, the frame transmission, and any acknowledgment can be completed before the end of the CAP, and the frame transmission will start in one of the first *macBattLifeExtPeriods* full backoff periods after the IFS period following the beacon. If the MAC sublayer can proceed, it shall request that the PHY perform the CCA in the current superframe. If the MAC sublayer cannot proceed, it shall wait until the start of the CAP in the next superframe and apply a further random backoff delay before evaluating whether it can proceed again.

10.12 Suspendable CSMA-CA algorithm

10.12.1 Overview of suspendable CSMA-CA algorithm

Suspendable CSMA-CA is an optional modification to the standard CSMA-CA algorithm to support deployment in Japan and other regions, where backoff suspension is needed.

10.12.2 Channel access when using suspendable CSMA-CA algorithm

Optional backoff suspension can improve performance of networks by reducing the probability of CSMA-CA algorithm failure when the network is congested and/or when the network coexists with aggressive interfering networks. The use of the suspendable CSMA-CA algorithm is signaled during the association process as described in 10.21.5.1 and 10.4.12.1. The suspendable CSMA-CA algorithm is enabled when *macSuspendedCsma* is TRUE. When *macSuspendedCsma* is TRUE, slotted and unslotted CSMA will proceed as in Figure 6-2 with the following additional steps:

- CCA Mode 1, 2, or 3 shall be used.
- The channel will be sensed using the selected CCA mode during the backoff delay period within each unit backoff period. If CCA is busy during the backoff delay period, the backoff timer shall be suspended until sensing the channel indicates that the channel is clear or *macSuspendedCsmaMaxTime* is exceeded. Upon CCA detecting clear, the backoff timer shall resume. If *macSuspendedCsmaMaxTime* is exceeded, the algorithm shall end in “Failure” and terminates with a channel access failure.

10.12.3 MAC constants and PIB attributes for suspendable CSMA-CA algorithm

PIB attributes related to the suspendable CSMA-CA algorithm are described in the Table 10-65.

Table 10-65—MAC PIB attributes for suspendable CSMA-CA algorithm

Attribute	Type	Range	Description	Default
<i>macSuspendedCsma</i>	Boolean	TRUE, FALSE	Indication whether the suspendable CSMA-CA algorithm is enabled or not.	FALSE
<i>macSuspendedCsmaMaxTime</i>	Integer	Implementation dependent	Timeout value for suspending backoff timer.	Implementation dependent

10.13 Rail communications and control network (RCCN)

10.13.1 Overview of RCCN

RCC refers to a wireless information exchange and sensor or control communications deployed in applications such as the following:

- A wireless link between trains, locomotives, or other mobile rolling stock to fixed trackside or network infrastructure
- A link between connected fixed, remote trackside infrastructure, and fixed network infrastructure
- A link between vehicles in the same train or between two or more trains

RCC devices are intended to support mobile rail vehicle communications at high speeds with data rates that enable connections at distances of over 50 km. The RCC PHYs are designed to take advantage of relatively small amounts of spectrum where spectrum is costly or scarce.

10.13.2 Rail communications and control network (RCCN) superframe structure

Support for the rail communications and control network (RCCN) superframe structure is optional for an RCC device. For typical usage, refer to “Application of IEEE Std 802.15.4” [B4].

The RCCN superframe structure is shown in Figure 10-128.

The duration of an RCCN superframe slot is as follows:

$$(k + 1) \times aRccnBaseSlotDuration$$

where k is the value of the Slot Size Multiplier field of the RCCN descriptor IE, as described in 10.13.3.2.

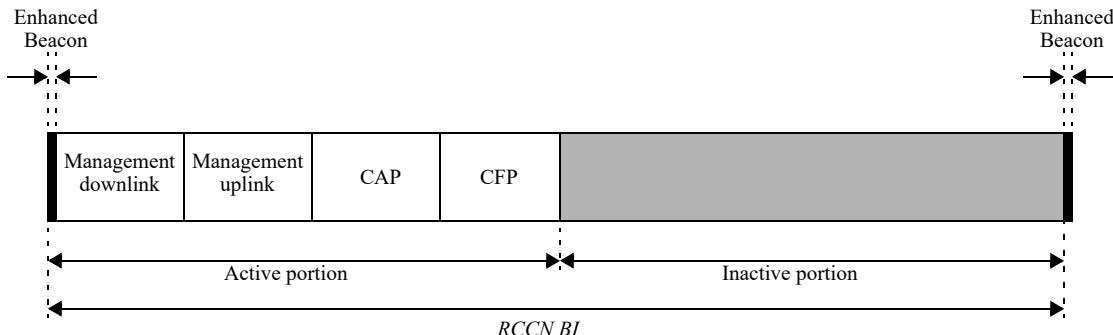


Figure 10-128—RCCN superframe structure

The superframe begins with an enhanced beacon containing the RCCN descriptor IE. The management downlink slots are used by the RCCN PAN coordinator to send frames to RCCN endpoints, while the management uplink slots are used by RCCN endpoints to send frames to the RCCN PAN coordinator. Channel access in the management uplink slots is performed using slotted CSMA-CA. Following the uplink slots is the CAP, in which communication between any devices in the RCCN may occur; channel access is gained using slotted CSMA-CA, optionally with PCA, as described in 10.10.2.1. Following the CAP is a CFP containing one or more GTSs allocated by the RCCN PAN coordinator.

10.13.3 Header IEs for RCCN

10.13.3.1 RCC Capabilities IE

The presence of this IE in a transmitted frame indicates that the coordinator supports an RCC PHY. The RCC Capabilities IE Content field shall be formatted as shown in Figure 10-129.

Octets: 2	2	2
RCC Frequency Bands Supported	RCC PHY and Modulation Supported	RCC DSSS DPSK Modulation Supported

Figure 10-129—RCC Capabilities IE Content field format

The RCC Frequency Bands Supported field shall be formatted as given in Table 10-66.

Table 10-66—RCC Frequency Bands Supported field encoding

Bit number	Description
0	161 MHz band supported
1	216 MHz band supported
2	217 MHz band supported
3	220 MHz band supported
4	450 MHz band supported
5	770 MHz band supported
6	800 MHz band supported
7	806 MHz band supported
8	896 MHz band supported
9	915 MHz band supported
10	928 MHz band supported
11	2450 MHz band supported
12	4965 MHz band supported
13	5800 MHz band supported
14–15	Reserved

The RCC PHY and Modulation Supported field shall be formatted as given in Table 10-67.

Table 10-67—RCC PHY and Modulation Supported field encoding

Bit number	Description
0	LMR GMSK 9.6 kb/s supported
1	LMR GMSK 19.2 kb/s supported
2	LMR 4-FSK 9.6 kb/s supported
3	LMR 4-FSK 19.2 kb/s supported
4	LMR 4-FSK 38.4 kb/s supported
5	LMR QPSK 16 kb/s supported
6	LMR QPSK 32 kb/s supported
7	LMR $\pi/4$ DQPSK 16 kb/s supported
8	LMR $\pi/4$ DQPSK 32 kb/s supported
9	LMR $\pi/4$ DQPSK 36 kb/s supported
10	LMR DSSS DPSK supported
11	LMR DSSS BPSK supported
12–15	Reserved

The RCC DSSS differential phase-shift keying (DPSK) Modulation Supported field shall be formatted as given in Table 10-68.

Table 10-68—RCC DSSS DPSK Modulation Supported field encoding

Bit number	Description
0	300 kcps chip rate supported
1	600 kcps chip rate supported
2	800 kcps chip rate supported
3	1 Mcps chip rate supported
4	1.6 Mcps chip rate supported
5	2 Mcps chip rate supported
6	3 Mcps chip rate supported
7	4 Mcps chip rate supported
8	11-chip spreading sequence supported
9	15-chip spreading sequence supported
10	20-chip spreading sequence supported
11	40-chip spreading sequence supported
12	DSSS DBPSK supported
13	DSSS DQPSK supported
14–15	Reserved

10.13.3.2 RCCN Descriptor IE

The RCCN Descriptor IE Content field shall be formatted as shown in Figure 10-130.

Octets: 1	2	4	1	1	variable
Version	Slot Size Multiplier	RCCN Slots	Inactive Duration	Network ID Length	Network ID

Figure 10-130—RCCN Descriptor IE Content field format

The Version field indicates the version of the RCCN descriptor IE and shall be set to zero for this version of the standard.

The Slot Size Multiplier field is used to calculate the superframe slot duration, as described in 10.13.2.

The RCCN Slots field shall be formatted as shown in Figure 10-131.

Octets: 1	1	1	1
Management Downlink Slots	Management Uplink Slots	CAP Slots	CFP Slots

Figure 10-131—RCCN Slots field format

The Management Downlink Slots field indicates the number of superframe slots allocated to the PAN coordinator for the purpose of sending frames to RCCN endpoints.

The Management Uplink Slots field indicates the number of superframe slots allocated to RCCN endpoints for the purposes of sending frames to the RCCN PAN coordinator.

The CAP Slots field indicates the number of superframe slots allocated to the CAP.

The CFP Slots field indicates the number of superframe slots allocated to the CFP.

The Inactive Duration field specifies the length, in units of superframe slot duration, of the inactive portion of the superframe structure.

The Network ID Length field indicates the length of the Network ID field.

The Network ID field contains a set of octets that contain a network-specific identification. The value of the field shall be set to *macRccnNetId*.

10.13.4 Nested IEs for RCCN

10.13.4.1 RCC PHY Operating Mode IE

The RCC PHY Operating Mode IE Content field shall be formatted as shown in Figure 10-132.

Bits: 0–13	14–18	19–22	23–25	26–27	28–31
Channel Number	Operating Band	PHY/Modulation	Chip Rate	Spreading Sequence	Reserved

Figure 10-132—RCC PHY Operating Mode IE Content field format

The Channel Number field contains a valid channel number for an RCC PHY, as defined in 11.1.3.12.

The Operating Band field shall be set to the current operating band where the bands are defined as the integers greater than zero that correspond to the bit numbers given in Table 10-66.

The PHY/Modulation field shall be set to the current PHY and modulation where the value corresponds to the bit number given in Table 10-67.

The Chip Rate field is valid for the land mobile radio (LMR) PHY and is reserved otherwise. Valid values for the Chip Rate field are given in Table 10-69.

Table 10-69—Chip Rate field values

Field value	Definition
0	300 kchip/s
1	600 kchip/s
2	800 kchip/s
3	1 Mchip/s
4	1.6 Mchip/s
5	2 Mchip/s
6	3 Mchip/s
7	4 Mchip/s

The Spreading Sequence field is valid for the LMR PHY and is reserved otherwise. Valid values for the Spreading Sequence field are given in Table 10-70.

Table 10-70—Spreading Sequence field values

Field value	Definition
0	11-chip
1	15-chip
2	20-chip
3	40-chip

10.13.5 MAC constants and PIB attributes for RCCN

RCCN related MAC PIB constants are provided in Table 10-71, and Table 10-72 provides RCCN related MAC PIB attributes. For explanation of dagger (\dagger) and asterisk (*) symbols see 8.4.3.1.

Table 10-71—RCCN related MAC PIB constants

Constant	Description	Value
<i>aRccnBaseSlotDuration</i>	The number of symbols forming an RCCN superframe slot.	60

Table 10-72—RCCN related MAC PIB attributes

Attribute	Type	Range	Description	Default
<i>macRccnNumTimeSlots</i>	Integer	0–254	The number of timeslots within a superframe, excluding the timeslot for beacon frame and management timeslots.	48
<i>macRccnNumMgmtTs</i>	Integer	0–254	The number of management timeslots.	4
<i>macRccnNumGtsTs</i>	Integer	0–254	The number of GTS timeslots.	24
<i>macRccnNetId</i>	Set of octets	—	A network specific identification.	0
<i>macRccnDevType</i>	Enumeration	RCCPANC, MOBILE, FIXED	Indicates the type of RCCN device. It may be one of the following device types: a PAN coordinator, a mobile device that is not a PAN coordinator, or a fixed device that is not a PAN coordinator.	—
<i>macRccnCap</i>	List of octets \dagger	—	The PHY capabilities supported.	—

10.14 Smart utility network (SUN)

10.14.1 Overview of SUN

SUNs enable multiple applications to operate over shared network resources, providing monitoring and control of a utility system. SUN devices are designed to operate in very large-scale, low-power wireless applications and often require using the maximum transmit power available under applicable regulations, in order to provide long-range, point-to-point connections. Frequently, SUNs are required to cover geographically widespread areas containing a large number of outdoor devices. In these cases, SUN devices typically employ mesh or peer-to-peer multihop techniques to communicate with an access point.

10.14.2 Starting a PAN in SUN

If the device is operating as a coordinator, a passive scan for a Coexistence Specification IE should take place prior to the active channel scan, as described in 6.4.1.2.

10.14.3 Nested IEs for SUN

10.14.3.1 SUN Device Capabilities IE

The SUN Device Capabilities IE Content field shall be formatted as illustrated in Figure 10-133.

Octets: 1	2/4	variable
SUN Features	Frequency Bands Supported	PHY Type Descriptor(s)

Figure 10-133—SUN Device Capabilities IE Content field format

The SUN Features field shall be formatted as illustrated in Figure 10-134.

Bits: 0	1	2	3	4	5	6	7
Enh-Ack	Data Whitening	Interleaving	SFD G1	NRNSC FEC	RSC FEC	Mode Switch	Extended Band Identifier

Figure 10-134—SUN Features field format

The Enh-Ack field shall be set to one if the Enh-Ack frame, as described in 6.6.3.3, is supported and shall be set to zero otherwise.

The Data Whitening field shall be set to one if data whitening, as described in 20.4, is supported and shall be set to zero otherwise.

The Interleaving field shall be set to one if interleaving, as described in 20.3.6, is supported and shall be set to zero otherwise.

The SFD G1 field shall be set to one if the SFD group 1, as described in 20.2.2.3, is supported and shall be set to zero otherwise.

The nonrecursive and nonsystematic code (NRNSC) FEC field shall be set to one if the NRNSC FEC, as described in 20.3.5, is supported and shall be set to zero otherwise.

The recursive and systematic code (RSC) FEC field shall be set to one if the recursive and systematic code (RSC) FEC, as described in 20.3.5, is supported and shall be set to zero otherwise.

The Mode Switch field shall be set to one if the mode switch mechanism, as described in 20.5, is supported and shall be set to zero otherwise.

If Extended Band Identifier field is set to zero, then the Frequency Bands Supported field in Figure 10-133 is 2 octets long with the frequency band identifier values given in Table 10-73. Otherwise, if Extended Band Identifier field is set to one, then the Frequency Bands Supported field in Figure 10-133 is 4 octets long with the extended frequency band identifier values given in Table 10-73 and Table 10-74.

The Frequency Bands Supported field is a bitmap indexed by the frequency band identifier values given in Table 10-73 and Table 10-74. The least significant bit of the bitmap corresponds to frequency band identifier zero. A bit set to one indicates that the device supports operation in that frequency band; otherwise, it does not.

Table 10-73—Frequency band identifier values

Frequency band identifier	Band designation
0	169 MHz
1	450 MHz
2	470 MHz
3	780 MHz
4	863 MHz
5	896 MHz
6	901 MHz
7	915 MHz
8	917 MHz
9	920 MHz
10	928 MHz
11	920 MHz
12	1427 MHz
13	2450 MHz
14	866 MHz
15	870 MHz

Table 10-74—Frequency band identifier values—extended

Frequency band identifier—extended	Band designation
16	915 MHz-a
17	915 MHz-b
18	915 MHz-c
19	915 MHz-d
20	915 MHz-e
21	919 MHz
22	920 MHz-a
23	920 MHz-b
24	867 MHz
25–31	Reserved

The PHY Type Descriptor field shall be formatted as illustrated in Figure 10-135.

Bits: 0–3	4	5–15	Octets: 2/4
PHY Type	All Frequency Bands	PHY Modes Supported (PHY Mode ID bitmap: b0...b10)	Specific Frequency Bands (only present if All Frequency Bands = 0)

Figure 10-135—PHY Type Descriptor field format

The PHY Type field contains an unsigned integer whose value identifies a PHY Type defined in Table 10-75.

Table 10-75—Modulation scheme encoding

PHY type	Modulation scheme
0	FSK-A
1	FSK-B
2	O-QPSK-A
3	O-QPSK-B
4	O-QPSK-C
5	OFDM Option 1
6	OFDM Option 2
7	OFDM Option 3

Table 10-75—Modulation scheme encoding (continued)

PHY type	Modulation scheme
8	OFDM Option 4
9	FSK-C
10–15	Reserved

The All Frequency Bands field indicates whether the optional Specific Frequency Bands field is present. If the All Frequency Bands field is set to one, the optional Specific Frequency Bands field is absent and the PHY Type is supported in all frequency bands declared in the Frequency Bands Supported field of the SUN device capabilities IE. If the All Frequency Bands field is set to zero, the optional Specific Frequency Bands field is present, and the PHY Type is only supported in the frequency bands declared in the Specific Frequency Bands field of this PHY Type Descriptor.

The PHY Modes Supported field is a bitmap indicating which PHY modes are supported for the PHY Type. The PHY modes for each possible PHY Type are defined in Table 10-76, Table 10-77, Table 10-78, Table 10-79, Table 10-80, Table 10-81, and Table 10-82. A bit set to one in bit b_n of the PHY Mode ID bitmap indicates that the PHY Mode with ID n in the table of PHY Modes corresponding to the PHY Type is supported; otherwise, it is not supported.

The optional Specific Frequency Bands field is encoded in the same manner as the Frequency Bands Supported field of the SUN Device Capabilities IE.

The FSK-A PHY mode encodings are defined in Table 10-76.

Table 10-76—FSK-A PHY mode encoding

PHY Mode ID	Narrowband FSK PHY mode
0	4.8 kb/s; 2-FSK; mod index = 1.0; channel spacing = 12.5 kHz
1	9.6 kb/s; 4-FSK; mod index = 0.33; channel spacing = 12.5 kHz
2	10 kb/s; 2-FSK; mod index = 0.5; channel spacing = 12.5 kHz
3	20 kb/s; 2-FSK; mod index = 0.5; channel spacing = 12.5 kHz
4	40 kb/s; 2-FSK; mod index = 0.5; channel spacing = 12.5 kHz
5	4.8 kb/s; 2-FSK; mod index = 0.5; channel spacing = 12.5 kHz
6	2.4 kb/s; 2-FSK; mod index = 2.0; channel spacing = 12.5 kHz
7	9.6 kb/s; 4-FSK; mod index = 0.33; channel spacing = 12.5 kHz
8–10	Reserved

The FSK-B PHY mode encodings are defined in Table 10-77.

Table 10-77—FSK-B PHY mode encoding

PHY Mode ID	FSK PHY mode
0	50 kb/s; 2-FSK; mod index = 1.0; channel spacing = 200 kHz
1	100 kb/s; 2-FSK; mod index = 1.0; channel spacing = 400 kHz
2	150 kb/s; 2-FSK; mod index = 0.5; channel spacing = 400 kHz
3	200 kb/s; 2-FSK; mod index = 0.5; channel spacing = 400 kHz
4	200 kb/s; 4-FSK; mod index = 0.33; channel spacing = 400 kHz
5	200 kb/s; 2-FSK; mod index = 1.0; channel spacing = 600 kHz
6	400 kb/s; 4-FSK; mod index = 0.33; channel spacing = 600 kHz
7	100 kb/s; 2-FSK; mod index = 0.5; channel spacing = 200 kHz
8	50 kb/s; 2-FSK; mod index = 0.5; channel spacing = 100 kHz
9	150 kb/s; 2-FSK; mod index = 0.5; channel spacing = 200 kHz
10	300 kb/s; 2-FSK; mod index = 0.5; channel spacing = 400 kHz

The FSK-C PHY mode encodings are defined in Table 10-78.

Table 10-78—FSK-C PHY mode encoding

PHY Mode ID	FSK PHY mode
0	10 kb/s; 2-FSK; mod index = 1.0; channel spacing = 50 kHz
1	20 kb/s; 2-FSK; mod index = 1.0; channel spacing = 100 kHz
2	300 kb/s; 2-FSK; mod index = 0.5; channel spacing = 600 kHz
3	400 kb/s; 4-FSK; mod index = 0.33; channel spacing = 400 kHz
4	400 kb/s; 2-FSK; mod index = 0.5; channel spacing = 1000 kHz
5	600 kb/s; 2-FSK; mod index = 0.4; channel spacing = 1000 kHz
6	600 kb/s; 4-FSK; mod index = 0.5; channel spacing = 1000 kHz
7	800 kb/s; 4-FSK; mod index = 0.33; channel spacing = 1000 kHz
8–10	Reserved

The O-QPSK-A PHY mode encodings are defined in Table 10-79.

Table 10-79—O-QPSK-A PHY mode encoding

PHY Mode ID	Narrowband O-QPSK PHY mode
0	chip rate = 100 kchip/s; SpreadingMode = DSSS; RateMode = 0; data rate = 6.25 kb/s
1	chip rate = 100 kchip/s; SpreadingMode = DSSS; RateMode = 1; data rate = 12.5 kb/s
2	chip rate = 100 kchip/s; SpreadingMode = DSSS; RateMode = 2; data rate = 25 kb/s
3	chip rate = 100 kchip/s; SpreadingMode = DSSS; RateMode = 3; data rate = 50 kb/s
4–10	Reserved

The O-QPSK-B PHY mode encodings are defined in Table 10-80.

Table 10-80—O-QPSK-B PHY mode encoding

PHY Mode ID	O-QPSK PHY mode
0	chip rate = 1000 kchip/s; SpreadingMode = DSSS; RateMode = 0; data rate = 31.25 kb/s
1	chip rate = 1000 kchip/s; SpreadingMode = DSSS; RateMode = 1; data rate = 125 kb/s
2	chip rate = 1000 kchip/s; SpreadingMode = DSSS; RateMode = 2; data rate = 250 kb/s
3	chip rate = 1000 kchip/s; SpreadingMode = DSSS; RateMode = 3; data rate = 500 kb/s
4	chip rate = 1000 kchip/s; SpreadingMode = MDSSS; RateMode = 0; data rate = 62.5 kb/s
5	chip rate = 1000 kchip/s; SpreadingMode = MDSSS; RateMode = 1; data rate = 125 kb/s
6	chip rate = 1000 kchip/s; SpreadingMode = MDSSS; RateMode = 2; data rate = 250 kb/s
7	chip rate = 1000 kchip/s; SpreadingMode = MDSSS; RateMode = 3; data rate = 500 kb/s
8–10	Reserved

The O-QPSK-C PHY mode encodings are defined in Table 10-81.

Table 10-81—O-QPSK-C PHY mode encoding

PHY Mode ID	O-QPSK PHY mode
0	chip rate = 2000 kchip/s; SpreadingMode = DSSS; RateMode = 0; data rate = 31.25 kb/s
1	chip rate = 2000 kchip/s; SpreadingMode = DSSS; RateMode = 1; data rate = 125 kb/s
2	chip rate = 2000 kchip/s; SpreadingMode = DSSS; RateMode = 2; data rate = 250 kb/s
3	chip rate = 2000 kchip/s; SpreadingMode = DSSS; RateMode = 3; data rate = 500 kb/s
4	chip rate = 2000 kchip/s; SpreadingMode = MDSSS; RateMode = 0; data rate = 62.5 kb/s
5	chip rate = 2000 kchip/s; SpreadingMode = MDSSS; RateMode = 1; data rate = 125 kb/s

Table 10-81—O-QPSK-C PHY mode encoding (continued)

PHY Mode ID	O-QPSK PHY mode
6	chip rate = 2000 kchip/s; SpreadingMode = MDSSS; RateMode = 2; data rate = 250 kb/s
7	chip rate = 2000 kchip/s; SpreadingMode = MDSSS; RateMode = 3; data rate = 500 kb/s
8–10	Reserved

For each OFDM option, the supported MCSs are defined in Table 10-82.

Table 10-82—OFDM PHY mode encoding

PHY Mode ID	OFDM PHY modes (Option 1, 2, 3, 4)
0	MCS0 supported
1	MCS1 supported
2	MCS2 supported
3	MCS3 supported
4	MCS4 supported
5	MCS5 supported
6	MCS6 supported
7–10	Reserved

In each encoding of PHY modes in the PHY Type Descriptor field, a bit set to one in a bit position corresponding to a given modulation scheme in Table 10-76, Table 10-77, Table 10-79, Table 10-80, Table 10-81, and Table 10-82 indicates the PHY mode for that modulation scheme is supported. A value of zero similarly indicates that the PHY mode is not supported.

The value of the SUN PHY Capabilities IE length field is computed as follows:

$$\text{Length} = 1 + 2 + 2 \times \text{NumPHYTypeAllFreq1} + 4 \times \text{NumPHYTypeAllFreq0}$$

where

$\text{NumPHYTypeAllFreq1}$ is the number of PHY Type Descriptor fields that have the All Frequency Bands field set to one.

$\text{NumPHYTypeAllFreq0}$ is the number of PHY Type Descriptor fields that have the All Frequency Bands field set to zero.

10.14.3.2 SUN FSK Generic PHY IE

The SUN FSK Generic PHY IE Content field shall be formatted as illustrated in Figure 10-136.

Octets: 1			1		4	2	4	4
Bits: 0–1	2–3	4–7	Bit #: 0–5	6–7				
Reserved	Modulation Scheme	SUN FSK Generic PHY ID	Modulation Index	BT	First Channel Center Frequency	Number of Channels	Channel Spacing	Symbol Rate

Figure 10-136—SUN FSK Generic PHY IE Content field format

The Modulation Scheme field is an unsigned integer that shall be to zero to indicate 2-FSK and shall be set to one to indicate 4-FSK. All other values are reserved.

SUN FSK Generic PHY ID field is an unsigned integer that is used to identify the PHY configuration contained in this IE.

The Modulation Index field is encoded as an unsigned integer with permissible values in the range 0–45. Values in the range 46–63 are undefined. The value of the modulation index for 2-FSK is computed using the value of the Modulation Index field in the following way:

$$\text{modulation index} = 0.25 + (\text{Modulation Index field value}) \times 0.05$$

For example, a modulation index of 0.5 would be encoded as 0b00101.

The BT field is an unsigned integer. The BT field shall be set to zero if the BT is 0.5 and shall be set to one if the BT is 1.0. All other values are reserved.

The First Channel Center Frequency field contains an unsigned integer whose value is the center frequency of the first channel in hertz.

The Number of Channels field contains an unsigned integer whose value is the number of channels for the generic PHY.

The Channel Spacing field contains an unsigned integer whose value is the difference between adjacent channel center frequencies in hertz. For example, 300 kHz channel spacing would be encoded as 0x493e0.

The Symbol Rate field contains an unsigned integer whose value is the number of symbols transmitted per second. For example, 100 ksymbol/s would be encoded as 0x186a0.

10.14.3.3 Mode Switch Parameter IE

The Mode Switch Parameter IE Content field shall be formatted as illustrated in Figure 10-137.

Octets: 1				1	1
Bits: 0	1–4	5	6–7	Settling Delay	Secondary FSK Preamble Length
Secondary FSK SFD	Target Mode	Source Mode	Mode Switch Parameter Index		

Figure 10-137—Mode Switch Parameter IE Content field format

The Secondary FSK SFD field value is set to one if a secondary SFD is present; otherwise, it is set to zero, as described in Table 12-13.

The Target Mode field contains an unsigned integer indicating the PHY Mode of the new mode PPDU. The values are as defined in Table 10-75.

The Source Mode field contains the mode that is used to transmit the mode switch PPDU. It is set to zero for 2-FSK or to one for 4-FSK.

The Mode Switch Parameter Index field contains an unsigned integer whose value is the index into the *phySunModeSwitchParameterEntries* PIB attribute array containing the mode switch parameter.

The Settling Delay field contains an unsigned integer whose value times two is the settling delay in microseconds (0–510 μ sec), as described in Table 12-13.

The Secondary FSK Preamble Length field contains an unsigned integer whose value is the number of preamble repetitions for the secondary preamble when the new mode is SUN FSK, as described in Table 12-13.

10.15 Low-energy, critical infrastructure monitoring (LECIM)

10.15.1 Overview of LECIM

The LECIM portions of this standard are designed to implement a minimal network infrastructure that enables the collection of scheduled and event data from a large number of non-mains powered end points that are widely dispersed, or are in challenging propagation environments. To facilitate low energy operation necessary for multi-year battery life, MAC protocols that minimize network maintenance traffic and device wake durations have been defined.

LECIM networks primarily operate in a star topology. LECIM networks are typically asymmetric in energy supply and capability, having a PAN coordinator that is mains powered (or otherwise provided a substantial power source) and energy and/or cost constrained devices. The PAN coordinator typically monitors the channel more often than a device. A device may sleep unless it has a Data frame to send.

10.15.2 Header IEs for LECIM

10.15.2.1 Fragment Sequence Context Description (FSCD) IE

The FSCD IE Content field shall be formatted as illustrated in Figure 10-138.

Octets: 2								2	...
Bits: 0	1	2–6	7–12	13–14	15	16–25	26–31		
Reserved	Secure Fragment	Reserved	TID	Frak Policy	FICS Length	PSDU Size	Addressing Information	...	

...	variable	0/4	
	Bits: 0–25	26–31	
...	Addressing	PSDU Counter	Reserved

Figure 10-138—FSCD IE Content field format

The Secure Fragment field is used to indicate whether the fragments in this transaction will be sent with authentication. When set, the PSDU Counter field shall be present in the FSCD IE, and the fragment validation field shall be set to the MIC, as described in 23.3.5. The field shall be set to one when *phyPsduFragSecure* is set to TRUE.

A transaction identifier (TID) field value of zero indicates that the TID field will be a reserved field in the fragments that follow. When the TID field value is nonzero, the value identifies the fragment sequence. It associates the context information with each fragment in the transaction. The MAC sets the TID value and should assure that the current value is different from any other active transactions.

The Frak Policy field shall be set to one of the values given in Table 23-4.

If the Secure Fragment field is set to one, then the FICS length field specifies the length of the Frak Validation field in the Frak frames. The FICS Length field shall be set to zero if a 2-octet FICS is used and shall be set to one if the 4-octet FICS is used. If the Secure Fragment field is set to zero, the PSDU Counter field and the Reserved field of the FCSD Content field shall not be present.

The PSDU Size field contains the number of octets in the PSDU.

The Addressing Information field shall be formatted as illustrated in Figure 10-139.

Bit: 0	1	2–3	4–5
Source PAN ID Present	Destination PAN ID Present	Source Address Mode	Destination Address Mode

Figure 10-139—Addressing Information field format

The setting of the Addressing Information field shall be determined by the PAN ID and addressing mode fields of the PSDU being fragmented.

The Source PAN ID Present field shall be set to one if the source PAN ID is included in the Addressing field and shall be set to zero otherwise.

The Destination PAN ID Present field shall be set to one if the destination PAN ID is included in the Addressing field and shall be set to zero otherwise.

The Source Address Mode field shall be set to one of the values given in Table 7-3.

The Destination Address Mode field shall be set to one of the values given in Table 7-3.

The Addressing field contains source and/or destination addressing information associated with the MPDU being fragmented and shall be formatted as illustrated in Figure 10-140.

Octets: 0/2	0/2	0/2/8	0/2/8
Source PAN ID	Destination PAN ID	Source Address	Destination Address

Figure 10-140—Addressing field format

The content of this field shall be set according to the addresses contained in the MHR of the PSDU being fragmented. Addresses may be omitted to fit into the PSDU size of the PHY in use; algorithms for address suppression are implementation dependent.

The PSDU Counter field shall be present when the Secure Fragment field is set to one. The MAC shall maintain a counter that is incremented with each fragmentation transaction, initiated such that the counter value is not repeated, as described in 9.3.2.3.

10.15.2.2 LECIM Capabilities IE

The LECIM Capabilities IE Content field shall be formatted as illustrated in Figure 10-141.

Octets: 2	2	0/2	0/2	0/2
PHY Type and Bands Supported	LECIM PHY Features Supported	Lowest 2.4 GHz Channel	Highest 2.4 GHz Channel	LECIM PHY Extended Features Supported

Figure 10-141—Format of the LECIM Capabilities IE

In the PHY Type and Bands Supported field, bit 0 indicates the PHY type supported, which is the PHY type being described by the IE. A value of one indicates that LECIM FSK is described; a value of zero indicates that LECIM DSSS is described. Bits 1 to 12 to indicate support for different bands. A value of one indicates that a band is supported; a value of zero indicates that a band is not supported. The device shall indicate as supported only those bands that are implemented and defined for the indicated PHY type. The encoding for the field is shown in Table 10-83. Bit 15 indicates the support of LECIM PHY Extended Features, a value of zero indicates that LECIM PHY Extended Features are not supported; a value of one indicates that LECIM PHY Extended Features are supported.

Table 10-83—LECIM PHY Type and Bands Supported field encoding

Bit number	Description
0	PHY type described: 0 = LECIM DSSS 1 = LECIM FSK
1	Band 169 supported
2	Band 433 supported
3	Band 470 supported
4	Band 780 supported
5	Band 863 supported
6	Band 915 supported
7	Band 917 supported
8	Band 920 supported
9	Band 921 supported
10	Band 922 supported
11	Band 2450 supported
12	Band 262 supported
13–14	Reserved
15	LECIM PHY Extended Features supported

When the PHY Type and Bands Supported field indicates a LECIM DSSS PHY, the LECIM PHY Features Supported field shall be encoded as shown in Table 10-84. A value of one indicates that the feature is supported; a value of zero indicates that the feature is not supported.

Table 10-84—LECIM PHY Features Supported field encoding for DSSS

Bit number	Description
0	BPSK modulation supported
1	O-QPSK modulation supported
2–5	Maximum spreading factor supported; see Table 12-5 for the definition of <i>phyLecimDsssPsduSpreadingFactor</i>
6	16 octet PSDU supported
7	24 octet PSDU supported
8	32 octet PSDU supported
9	OVSF supported
10–15	Reserved

When the PHY Type and Bands Supported field indicates a LECIM FSK PHY, the LECIM PHY Features Supported field shall be encoded as shown in Table 10-85. A value of one indicates that the feature is supported; a value of zero indicates that the feature is not supported.

Table 10-85—LECIM PHY Features Supported field encoding for FSK

Bit number	Description
0	Positional modulation supported
1	Symbol rate 37.5 ksymbol/s supported, 200 kHz channel spacing ^a
2	Symbol rate 25 ksymbol/s supported, 200 kHz channel spacing ^a
3	Symbol rate 12.5 ksymbol/s supported, 200 kHz channel spacing ^a
4	Symbol rate 37.5 ksymbol/s supported, 100 kHz channel spacing ^a
5	Symbol rate 25 ksymbol/s supported, 100 kHz channel spacing ^a
6	Symbol rate 12.5 ksymbol/s supported, 100 kHz channel spacing ^a
7	Forward error correction (FEC) for non-split mode rate 1/2 convolutional code supported
8	Interleaving supported
9	Scrambling supported
10	SF 2 supported
11	SF 4 supported
12	SF 8 supported
13	SF 16 supported
14	Alternating SF pattern supported
15	Non-alternating SF pattern supported

^a Defined in 24.4.

The Lowest 2.4 GHz Channel and the Highest 2.4 GHz Channel fields specify the range of channels within the 2450 MHz band that are supported. These fields shall only be present when the PHY Type and Bands Supported field indicates support for the 2450 MHz band. The range of channels supported includes all of the channels starting from the channel number specified in the Lowest 2.4 GHz Channel field to the channel number specified in the Highest 2.4 GHz Channel field, inclusive.

When the PHY Type and Bands Supported field indicates that LECIM PHY Extended Features are supported, the LECIM PHY Extended Features Supported field shall be encoded as shown in Table 10-86. A value of one indicates that the feature is supported; a value of zero indicates that the feature is not supported. When the PHY Type and Bands Supported field indicates that LECIM PHY Extended Features are not supported, the LECIM PHY Extended Features Supported field shall not be present. *lecimBaseMultiplier* is defined in 11.1.3.11.3.

Table 10-86—Extended LECIM PHY Features Supported field encoding for FSK

Bit number	Description
0	Symbol rate 6.25 ksymbols/s supported, 200 kHz channel spacing
1	Symbol rate 6.25 ksymbols/s supported, 100 kHz channel spacing
2	Symbol rate $8 \times lecimBaseMultiplier$ ksymbols/s supported, $8 \times lecimBaseMultiplier$ kHz channel spacing
3	Symbol rate $4 \times lecimBaseMultiplier$ ksymbols/s supported, $4 \times lecimBaseMultiplier$ kHz channel spacing
4	Symbol rate $2 \times lecimBaseMultiplier$ ksymbols/s supported, $2 \times lecimBaseMultiplier$ kHz channel spacing
5	Symbol rate $lecimBaseMultiplier$ ksymbols/s supported, $lecimBaseMultiplier$ kHz channel spacing
6	Split mode supported
7	Split mode FEC rate 1/2 convolutional code supported
8	Split mode FEC rate 1/3 convolutional code supported
9	Split mode FEC rate 1/4 low density parity check (LDPC) code supported
10	SFD spreading supported
11	Symbol rate 2.4 ksymbols/s supported, 12.5 kHz channel spacing
12	Symbol rate 4.8 ksymbols/s supported, 12.5 kHz channel spacing
13–15	Reserved

10.15.3 Nested IEs for LECIM

10.15.3.1 LECIM DSSS Operating Mode IE

The LECIM DSSS Operating Mode IE Content field shall be formatted as illustrated in Figure 10-142.

Bits: 0–3	4–12	13	14–16	17	18–21	20	...
Operating Band	Channel Number	Modulation Selection	Chip Rate	Channel Spacing	PSDU Size	Preamble Present	...

...	21	22–25	26–29	30–53	54–63
...	SFD Present	Spreading Factor	OVSF Spreading Factor	Gold Code Initialization	Reserved

Figure 10-142—LECIM DSSS Operating Mode IE Content field

The Operating Band field contains an unsigned integer corresponding to a bit number given in Table 10-83. Values not corresponding to an assigned frequency band in Table 10-83 are reserved.

The Channel Number field contains the channel number, as defined in 11.1.3.11.2.

The Modulation Selection field shall be set to zero for BPSK and shall be set to one for O-QPSK.

The Chip Rate field is an unsigned integer that corresponds to the chip rate, as defined in Table 10-87:

Table 10-87—Chip Rate field valid values

Field value	Chip rate (kchips/s)
0	Reserved
1	100
2	200
3	400
4	600
5	800
6	1000
7	2000

The Channel Spacing shall be set to zero for 0.1 MHz channel spacing and shall be set to one for 0.2 MHz channel spacing.

The PSDU Size field shall be set to one of the values in Table 10-88.

Table 10-88—PSDU Size field valid values

Field value (b18 b19)	PSDU size
00	invalid
01	16 octets
10	24 octets
11	32 octets

The Preamble Present field shall be set to one if the preamble is present and shall be set to zero if the preamble is not present.

The SFD Present field shall be set to one if the SFD is present and shall be set to zero if the SFD is not present.

The Spreading Factor field contains *phyLecimDsssPsduSpreadingFactor*, as defined in Table 12-5.

The orthogonal variable spreading factor (OVSF) Spreading Factor field shall be set to one of the valid values defined in Table 10-89. All other values are reserved.

The Gold Code Initialization field shall be set to the Gold code LFSR2 initialization value, as specified in 23.2.7.2.

Table 10-89—OVSF Spreading Factor field values

Field value (b26 b27 b28 b29)	OVSF spreading factor
0000	OVSF not applied
0001	SF of 2
0010	SF of 4
0011	SF of 8
0100	SF of 16
0101	SF of 32
0110	SF of 64
0111	SF of 128
1000	SF of 256

10.15.3.2 LECIM FSK Operating Mode IE

The LECIM FSK Operating Mode IE Content field shall be formatted as illustrated in Figure 10-143.

Bits: 0–3	4–12	13	14–15	16	17	18	...
Operating Band	Channel Number	Position Modulation	Symbol Rate	Channel Spacing	FEC Enabled	Interleaving Enabled	...

...	19	20	21–22	23	24	25–31
...	Scrambler Enabled	Spreading Enabled	Spreading Factor	Spreading Pattern	SFD Spreading	Reserved

Figure 10-143—LECIM FSK Operating Mode IE Content field

The Operating Band field shall be set to an unsigned integer that corresponds to a bit number given in Table 10-83. Values not corresponding to a valid frequency band in Table 10-83 are reserved.

The Channel Number field is defined in 11.1.3.11.3.

The Position Modulation field shall be set to one if the position modulation is used and shall be set to zero otherwise.

The Symbol Rate field for 262 MHz band is an unsigned integer that corresponds to the symbol rate in Table 10-90.

The Symbol Rate field for other bands is an unsigned integer that corresponds to a symbol rate in Table 10-91.

Table 10-90—Symbol Rate field for 262 MHz band

Field value	Symbol rate
0	2.4 ksymbol/s
1	4.8 ksymbol/s
2	Reserved
3	Reserved

Table 10-91—Symbol Rate field for other bands

Field value	Symbol rate
0	37.5 ksymbol/s
1	25 ksymbol/s
2	12.5 ksymbol/s
3	6.25 ksymbol/s

The Channel Spacing field indicates the channel spacing in the operating band specified in this IE. When operating on 262 MHz band the Channel Spacing field is ignored, and channel spacing of 12.5 kHz is always used. In other bands, the Channel Spacing field shall be set to zero to indicate a 200 kHz channel spacing and shall be set to one to indicate a 100 kHz channel spacing.

The FEC Enabled field shall be set to one if FEC is enabled and shall be set to zero otherwise.

The Interleaving Enabled field shall be set to one if interleaving is enabled and shall be set to zero otherwise.

The Scrambler Enabled field shall be set to one if the scrambler is enabled and shall be set to zero otherwise.

The Spreading Enabled field shall be set to one if spreading is enabled and shall be set to zero otherwise.

The Spreading Factor field is an unsigned integer that corresponds to a spreading factor in Table 10-92.

Table 10-92—Spreading Factor field valid values

Field value	Spreading factor
0	2
1	4
2	8
3	16

The Spreading Pattern field shall be set to zero if a non-alternating spreading pattern is used and shall be set to one if an alternating spreading pattern is used.

The SFD Spreading field shall be set to one if spreading of the SFD is enabled and shall be set to zero otherwise.

10.15.3.3 LECIM FSK Split Operating Mode IE

The LECIM FSK Split Operating Mode IE Content field shall be formatted as illustrated in Figure 10-144.

Bits: 0–3	4–6	7–9	10–12	13	14–15	...
Operating Band	Symbol Rate	Channel Spacing	FEC Mode	Spreading Enabled	Spreading Factor	...

...	16	17–18	19–23	Octets: 2
...	Spreading Pattern	Radio-burst Distribution Method	Reserved	Channel Number

Figure 10-144—LECIM FSK Split Operating Mode IE Content field

The Operating Band field is an unsigned integer, and shall be set to a non-reserved bit number given in Table 10-83.

The Symbol Rate field is an unsigned integer that corresponds to a symbol rate in Table 10-93, *lecimBaseMultiplier* is defined in 11.1.3.11.3.

Table 10-93—Symbol Rate field valid values

Field value	Symbol rate
0	$8 \times \text{lecimBaseMultiplier}$ ksymbols/s
1	$4 \times \text{lecimBaseMultiplier}$ ksymbols/s
2	$2 \times \text{lecimBaseMultiplier}$ ksymbols/s
3	$\text{lecimBaseMultiplier}$ ksymbols/s
4–7	Reserved

The Channel Spacing field is an unsigned integer that corresponds to a channel spacing in Table 10-94, *lecimBaseMultiplier* is defined in 11.1.3.11.3.

Table 10-94—Channel Spacing field valid values

Field value	Symbol rate
0	$8 \times \text{lecimBaseMultiplier}$ kHz
1	$4 \times \text{lecimBaseMultiplier}$ kHz
2	$2 \times \text{lecimBaseMultiplier}$ kHz

Table 10-94—Channel Spacing field valid values (continued)

Field value	Symbol rate
3	$lecmBaseMultiplier$ kHz
4–7	Reserved

The FEC Mode field is an unsigned integer that corresponds to an FEC mode as given in Table 10-95.

Table 10-95—FEC Mode field valid values

Field value	FEC Mode rate
0	Rate 1/2 convolutional code
1	Rate 1/3 convolutional code
2	Rate 1/4 LDPC code
3–7	Reserved

The Spreading Enabled field shall be set to one if spreading is enabled and shall be set to zero otherwise.

The Spreading Factor field is an unsigned integer that corresponds to a spreading factor in Table 10-92.

The Spreading Pattern field shall be set to zero if a non-alternating spreading pattern is used and shall be set to one if an alternating spreading pattern is used.

The Radio-burst Distribution Method field is an unsigned integer that corresponds to a distribution method as given in Table 10-96.

The Channel Number field is defined in 11.1.3.11.3.

Table 10-96—Radio-burst Distribution Method field valid values

Field value	Radio-burst distribution method
0	CUSTOM
1	FIXED
2–3	Reserved

10.16 Channel hopping

10.16.1 Overview of channel hopping

Networks may support channel hopping using any multichannel PHY. Devices may hop in a slotted mode (e.g., TSCH or DSME) or in an unslotted mode.

The slotted mode uses network coordination within a superframe, for DSME, or slotframe, for TSCH, via a shared hop sequence to which devices participating in the network synchronize. Because the hop dwell time

is usually one slot time, the network synchronization covers the needs of hopping and timeslots. This mechanism allows a node to communicate with one or many other nodes. The unslotted mode does not use network synchronization for hopping, e.g., networks have many sequences without any global clock. For neighbor devices to communicate, a node needs to know the other nodes's hop sequence and timing. Devices may advertise their hop sequences and timing via the Channel Hopping IE and the Hopping Timing IE in Enhanced Beacon frames.

A specific hopping sequence is specified by its Hopping Sequence ID (*macHoppingSequenceId*) with ID = 0 denoting the default hop sequence for a particular PHY (or PHY configuration if the PHY supports more than one channel list). The hopping sequence characteristics are defined in Table 10-97.

This default hopping sequence is a pseudo-randomly shuffled set of all of the channels available to the PHY. The mechanism to generate the default sequence is defined as follows:

- SHUFFLE is a *macHoppingSequenceLength*-sized array. The contents of this array are equivalent to the first *macHoppingSequenceLength* outputs of a 9-bit linear feedback shift register (LFSR) with polynomial $x^9 + x^5 + 1$ and a starting seed of 255. Each LFSR output is modulo *macHoppingSequenceLength*, so that each entry of SHUFFLE is between 0 and (*macHoppingSequenceLength* – 1), inclusive.
- CHANNELS is a *macHoppingSequenceLength*-sized array that is initially populated with the monotonically increasing set of channels available to the PHY.
- CHANNELS is shuffled as per Figure 10-145. Elements may wind up being swapped multiple times in this process.
- The default sequence (i.e., *macHoppingSequenceList* for *macHoppingSequenceId* = 0) is equivalent to the shuffled CHANNELS array.

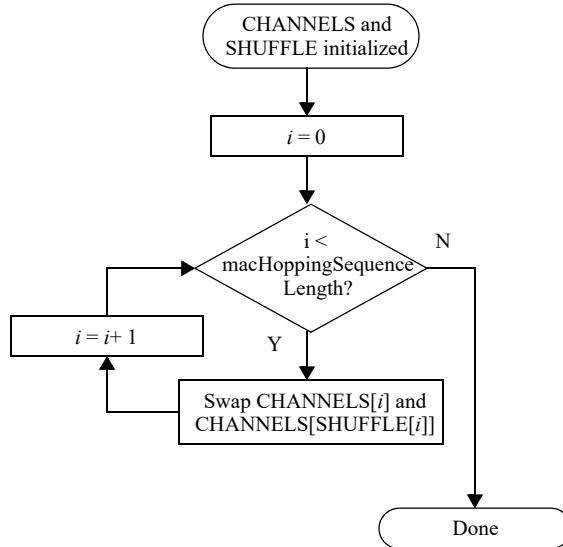


Figure 10-145—CHANNELS shuffle algorithm

The use of other sequences (*macHoppingSequenceId* > 0) may be defined by a particular channel hopping system. The *macHoppingSequenceList* for a *macHoppingSequenceId* > 0 may be longer or shorter than the default sequence and may be specified algorithmically or set as a predefined channel list. Two hopping devices cannot communicate unless their PHYs support the same number of channels, and they either use the default hopping sequence or agree upon the hopping sequence being used, either through carrying this information in an Enhanced Beacon frame, or through preconfiguration.

For cases where *macHoppingSequenceLength* is greater than the number of channels available to the PHY, this implies that some channels will appear multiple times in the array. For cases where *macHoppingSequenceLength* is less than or equal to the number of channels available to the PHY, some channels available to the PHY may be excluded from the array. The selection of channels (the subset of available PHY channels, and which, if any, channels are used multiple times in the hopping sequence) is implementation specific.

In general, a device can calculate the channel as follows:

$$CH = macHoppingSequenceList [COUNTER \% macHoppingSequenceLength]$$

where the COUNTER is some appropriate shared counter for a pair of devices communicating using that mode, and % indicates modular division.

10.16.2 Nested IEs for channel hopping

10.16.2.1 Channel Hopping IE

The Channel Hopping IE Content field shall be formatted as illustrated in Figure 10-146. The Channel Hopping IE may be sent with only the Hopping Sequence ID field to reduce the size of the beacon. Otherwise, all the fields are included.

Octets: 1	0/1	0/2	0/4	0/variable	0/2	0/variable	0/2
Hopping Sequence ID	Reserved	Number of Channels	PHY Configuration	Extended Bitmap	Hopping Sequence Length	Hopping Sequence	Current Hop

Figure 10-146—Channel Hopping Timing IE Content field format

The Hopping Sequence ID field shall be set equal to the value of *macHoppingSequenceId*.

The Number of Channels field shall be set equal to the value of *macNumberOfChannels*.

The PHY Configuration shall be set to *macPhyConfiguration*.

The Extended Bitmap field is valid only for SUN PHYs. The Extended Bitmap field contains *macExtendedBitmap*, which is a bitmap in which a bit is set to one if a channel is to be used and is set to zero otherwise. The Extended Bitmap field is *macNumberOfChannels* bits long, with additional bits added to make it an integer number of octets. For all other PHYs, it is zero length.

The Hopping Sequence Length field shall be set to the number of channels in the Hopping Sequence field.

The Hopping Sequence field is a set of unsigned integers, each two octets in length, that contains a channel number in the hopping sequence.

The Current Hop field shall be set to the index of the current position in the hopping sequence list.

10.16.3 MAC constants and PIB attributes for channel hopping

10.16.3.1 MAC PIB attributes for hopping sequence

The attributes contained in the MAC PIB for hopping sequence are presented in Table 10-97.

Table 10-97—MAC PIB attributes for hopping sequence

Attribute	Type	Range	Description	Default
<i>macHoppingSequenceId</i>	Integer	0x00–0x0f	The unique ID of the hopping sequence.	0
<i>macNumberOfChannels</i>	Integer	0x0000–0x01ff	Number of channels supported by the PHY.	—
<i>macPhyConfiguration</i>	Integer	0x00000000–0x7fffffff	For SUN PHYs, the 27 LSBs indicate the configuration of the PHY, and the channel list is contained in the Extended Bitmap field. For other PHYs the 27 LSBs (b0, b1, ..., b26) indicate the status (1 = to be used, 0 = not to be used) for each of the up to 27 channels available to the PHY.	—
<i>macExtendedBitmap</i>	Bitmap	Varies	For SUN PHYs a bitmap of <i>macNumberOfChannels</i> bits, where b_k shall indicate the status of channel k for each of the up to <i>macNumberOfChannels</i> valid channels supported by that phyConfiguration. Otherwise it is a null string.	—
<i>macHoppingSequenceLength</i>	Integer	0x0000–0xffff	The number of channels in the Hopping Sequence. Does not necessarily equal <i>macNumberOfChannels</i> .	—
<i>macHoppingSequenceList</i>	Set of integers	0x0000–0x01ff for each channel	A <i>macHoppingSequenceLength</i> -element set of channels to be hopped over.	—
<i>macHopDwellTime</i>	Integer	0x0000–0xffff	For unslotted channel hopping modes, this field is the channel dwell time, in units of 10 µs. For other modes, the field is empty.	—

10.17 PAN ID conflict resolution

10.17.1 General

In some instances a situation could occur in which two PANs exist in the same radio communications range with the same PAN ID. If this conflict happens, the PAN coordinator and its devices shall perform the PAN ID conflict resolution procedure.

10.17.2 Detection

The PAN coordinator shall conclude that a PAN ID conflict is present if either of the following apply:

- A Beacon frame is received by the PAN coordinator with the PAN Coordinator field, as defined in 7.3.1.4, set to one and the PAN ID equal to *macPanId*.
- A PAN ID Conflict Notification command, as defined in 10.17.4.1, is received by the PAN coordinator from a device associated with it on its PAN.

A device that is associated through the PAN coordinator (i.e., *macAssociatedPanCoord* is set to TRUE) shall conclude that a PAN ID conflict is present if the following applies:

- A Beacon frame is received by the device with the PAN Coordinator field set to one, the PAN ID equal to *macPanId*, and an address that is neither *macCoordShortAddress* nor *macCoordExtendedAddress*.

A device that is associated through a coordinator that is not the PAN coordinator is not required to detect a PAN ID conflict.

10.17.3 Resolution

On the detection of a PAN ID conflict by a device, it shall generate the PAN ID Conflict Notification command, as defined in 10.17.4.1, and send it to its PAN coordinator. Because the PAN ID Conflict Notification command has the AR field set to request an acknowledgment, the PAN coordinator shall confirm its receipt by sending an Ack frame. Once the device has received the Ack frame from the PAN coordinator, the MLME shall issue an MLME-SYNC-LOSS.indication primitive, as described in 10.2.10.3, with the LossReason parameter set to PAN_ID_CONFLICT. If the device does not receive an Ack frame, the MLME shall not inform the next higher layer of the PAN ID conflict.

On the detection of a PAN ID conflict by the PAN coordinator, the MLME shall issue an MLME-SYNC-LOSS.indication to the next higher layer with the LossReason parameter set to PAN_ID_CONFLICT. The next higher layer of the PAN coordinator can then perform an active scan and, using the information from the scan, select a new PAN ID. The algorithm for selecting a suitable PAN ID is outside the scope of this standard. If the next higher layer does select a new PAN ID, it may then issue an MLME-START-SUPERFRAME.request with the CoordRealignment parameter set to TRUE in order to realign the PAN, as described in 6.4.2.

10.17.4 MAC commands for PAN ID conflict resolution

10.17.4.1 PAN ID Conflict Notification command

The PAN ID Conflict Notification command has no Content field.

The Destination Addressing Mode and Source Addressing Mode fields shall both be set to indicate extended addressing.

The Frame Pending field shall be set to zero and ignored upon reception, and the AR field shall be set to one.

The Destination PAN ID field shall contain the value of *macPanId*, while the Source PAN ID field shall be omitted. The Destination Address field shall contain the value of *macCoordExtendedAddress*. The Source Address field shall contain the value of *macExtendedAddress*. The PAN ID Compression field shall be set as specified in 7.2.2.6.

10.18 ED channel scan

An ED scan allows a device to obtain a measure of the peak energy in each requested channel. This could be used by a prospective PAN coordinator to select a channel on which to operate prior to starting a new PAN. During an ED scan, the MAC sublayer shall discard all frames received over the PHY data service.

An ED scan over a specified set of channels is requested using the MLME-SCAN.request primitive with the ScanType parameter set to indicate an ED scan. For each channel, the MLME shall first switch to the channel, by setting *phyCurrentChannelInfo* accordingly, and then repeatedly perform an ED measurement for the value of the ScanDuration parameter in the MLME-SCAN.request primitive. The maximum ED measurement obtained during this period shall be passed to the next higher layer in MLME-SCAN.confirm as defined in 8.2.8.3.

The ED scan shall terminate when either the number of channel ED measurements stored equals the implementation-specified maximum or energy has been measured on each of the specified channels.

10.19 Active and enhanced active channel scan

An active channel scan allows a device to locate any coordinator transmitting Beacon frames within its radio communications range. An active scan uses the Beacon Request command to extract the beacon from a coordinator. A message sequence chart for an active scan is illustrated in Figure 10-147.

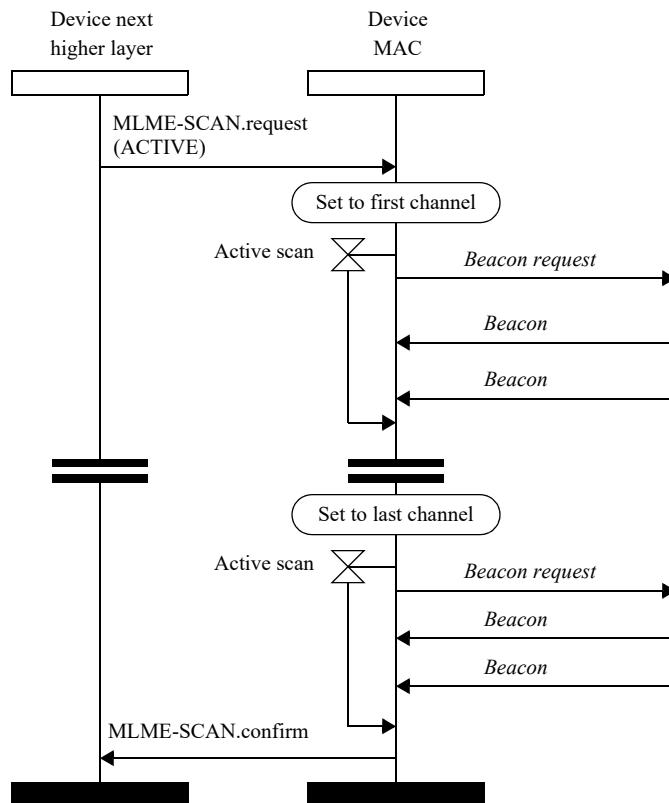


Figure 10-147—Active scan message sequence chart

During an active or an enhanced active scan, the frames received shall be processed as described in 6.4.1.2.

An active scan or an enhanced active scan over a specified set of channels is requested using the MLME-SCAN.request primitive with the ScanType parameter set to indicate an active scan or enhanced active scan, respectively. For each channel, the device shall first switch to the channel, by setting *phyCurrentChannelInfo* accordingly. For an active scan, the device shall send a Beacon Request command, as described in 7.5.2. For an enhanced active scan the device shall send an Enhanced Beacon Request command as described in 7.5.3.

For HRP UWB and CSS PHYs, the scan process shall be repeated for each mandatory preamble code, setting the *phyCurrentCode* appropriately.

If a coordinator of a PAN using superframe structure receives the Beacon Request command, it shall ignore the command and continue transmitting its periodic beacons as usual. If a coordinator of a PAN not using superframe structure receives this command, it shall transmit a single Beacon frame using unslotted CSMA-CA.

If a coordinator capable of responding to the Enhanced Beacon Request command, as described in 7.5.3, and capable of filtering receives an Enhanced Beacon Request command, it shall perform the filtering as indicated in the Enhanced Beacon Request command. If the filter conditions are satisfied, it shall transmit the appropriate Enhanced Beacon frame as indicated in Table 10-98.

Table 10-98—Channel access for response to an Enhanced Beacon Request command

Mode of operation	Access method	When to respond
Beacon PAN	Slotted CSMA-CA	Next available CAP
Nonbeacon PAN	Unslotted CSMA-CA	As soon as possible
DSME beacon	Slotted CSMA-CA	At the beginning of the next beacon interval
DSME non-beacon	Unslotted CSMA-CA	As soon as possible
TSCH	Slotted CSMA-CA	Next available timeslot on same channel

The messages exchanged when using an enhanced active scan with an Enhanced Beacon Request are shown in Figure 10-148.

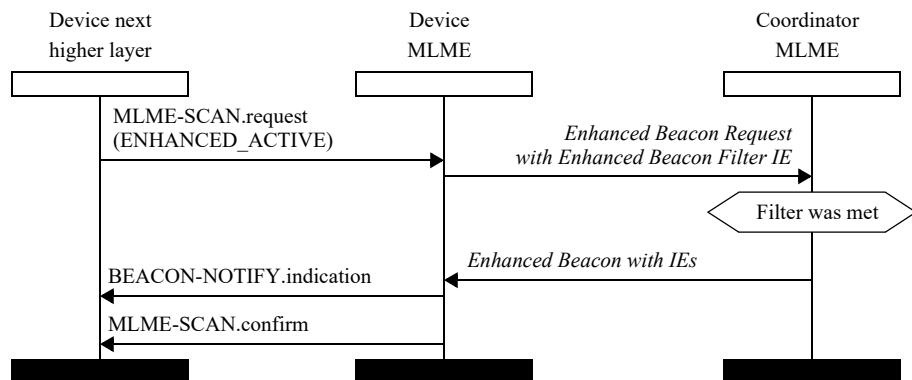


Figure 10-148—Enhanced active scan with Enhanced Beacon Request

10.20 Orphan channel scan

10.20.1 Overview of orphan channel scan

If the next higher layer receives repeated communications failures with a coordinator following its requests to transmit data, it may conclude that it has been orphaned. A single communications failure with a coordinator occurs when a device transaction fails to reach the coordinator; i.e., a requested acknowledgment is not received after *macMaxFrameRetries* attempts at sending the data. If the next higher layer concludes that it has been orphaned, it may instruct the MLME to either perform the orphaned device realignment procedure or reset the MAC sublayer and then perform the association procedure.

If the decision has been made by the next higher layer to perform the orphaned device realignment procedure, it will have issued an MLME-SCAN.request with the ScanType parameter set to orphan scan and the ScanChannel parameter containing the set of channels to be scanned. Upon receiving this primitive, the MAC sublayer shall begin an orphan scan, as described in 10.20.

If the orphan scan is successful (i.e., its PAN has been located), the device shall update its MAC PIB with the PAN information contained in the Coordinator Realignment command, as described in 7.5.4.

10.20.2 Channel access

10.20.2.1 Orphan channel scan

An orphan scan allows a device to attempt to relocate its coordinator following a loss of synchronization. During an orphan scan, the MAC sublayer shall discard all frames received over the PHY data service that are not Coordinator Realignment commands.

An orphan scan over a specified set of channels is requested using the MLME-SCAN.request primitive with the ScanType parameter set to indicate an orphan scan. For each channel, the device shall first switch to the channel, by setting *phyCurrentChannelInfo* accordingly, and for HRP UWB and CSS PHYs, setting the preamble code *phyCurrentCode* appropriately, and then send an Orphan Notification command, as described in 10.20.3.1. Upon successful transmission of the Orphan Notification command, the device shall enable its receiver for at most *macResponseWaitTime*. If the device successfully receives a Coordinator Realignment command, as described in 7.5.4, within this time, the device shall terminate the scan. For the HRP UWB and CSS PHYs, if the Coordinator Realignment command is not received, the process shall be repeated for each preamble code until a Coordinator Realignment command is received or all preamble codes for the PHY have been used.

The orphan scan shall terminate when the device receives a Coordinator Realignment command or the specified set of channels has been scanned.

A example message sequence chart for orphan scan and realignment is shown in Figure 10-149.

If a coordinator receives the Orphan Notification command, the MLME shall send the MLME-ORPHAN.indication primitive, as described in 10.20.4.2, to the next higher layer. The next higher layer should then search its device list for the device indicated by the primitive. If the next higher layer finds a record of the device, it should send a Coordinator Realignment command to the orphaned device using the MLME-ORPHAN.response primitive, as described in 10.20.4.3, with the AssociatedMember parameter set to TRUE and the ShortAddress parameter set to the corresponding short address allocated to the orphaned device. The process of searching for the device and sending the Coordinator Realignment command shall occur within *macResponseWaitTime*. The Coordinator Realignment command shall contain its current PAN ID, *macPanId*, its current channel, and the short address of the orphaned device. If the next higher layer of the coordinator finds no record of the device, it should send the MLME-ORPHAN.response primitive to the MLME with the AssociatedMember parameter set to FALSE.

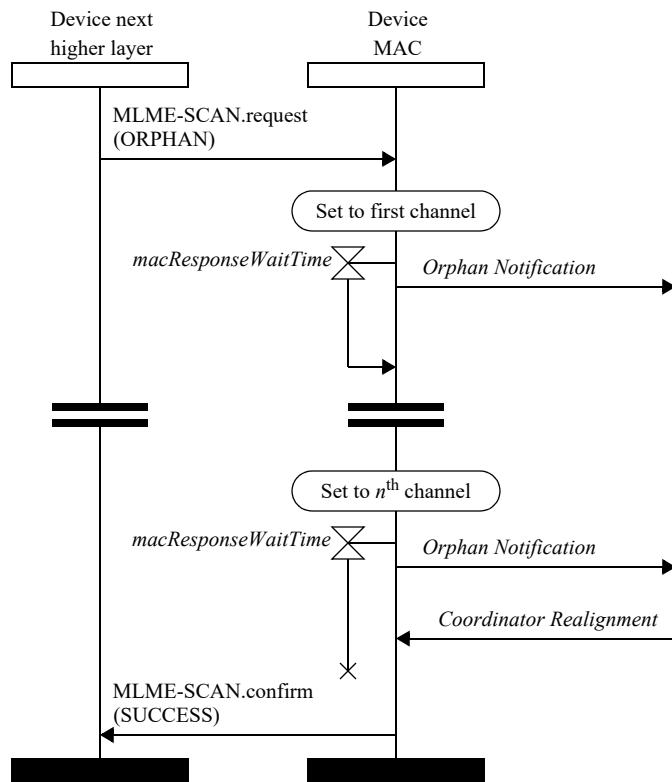


Figure 10-149—Orphaned device realignment message sequence chart

Figure 10-150 illustrates the sequence of messages necessary for a coordinator to issue a notification of an orphaned device.

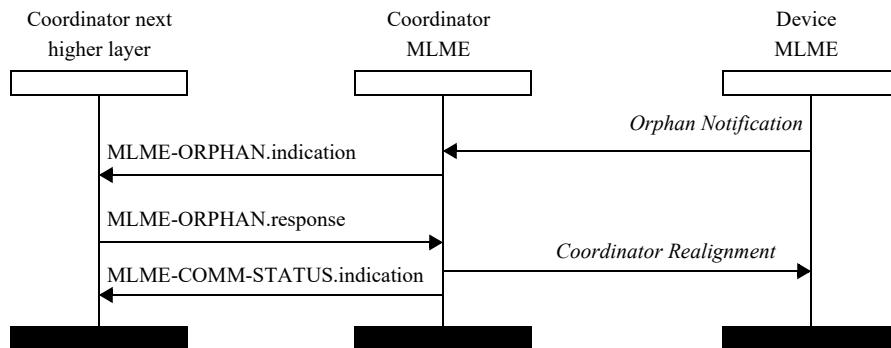


Figure 10-150—Message sequence chart for orphan notification

10.20.3 MAC commands for orphan channel scan

10.20.3.1 Orphan Notification command

The Orphan Notification command has no Content field.

The Source Addressing Mode field shall be set to indicate extended addressing. The Destination Addressing Mode field shall be set to indicate short addressing.

The Frame Pending field and AR field shall be set to zero and ignored upon reception.

The Destination PAN ID field shall contain the value of the broadcast PAN ID, while the Source PAN ID field shall be omitted. The Destination Address field shall contain the broadcast short address. The Source Address field shall contain the value of *macExtendedAddress*. The PAN ID Compression field shall be set as specified in 7.2.2.6.

10.20.4 MAC management service primitives for orphan channel scan

10.20.4.1 General

These primitives are used by a coordinator to issue a notification of an orphaned device.

10.20.4.2 MLME-ORPHAN.indication

The MLME-ORPHAN.indication primitive is generated by the MLME of a coordinator and issued to its next higher layer on receipt of an Orphan Notification command, as defined in 10.20.3.1.

The semantics of this primitive are as follows:

```
MLME-ORPHAN.indication      (
    OrphanAddress,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-99.

Table 10-99—MLME-ORPHAN.indication parameters

Name	Type	Valid range	Description
OrphanAddress	Extended address	Any valid extended address	The address of the orphaned device.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

10.20.4.3 MLME-ORPHAN.response

The MLME-ORPHAN.response primitive allows the next higher layer of a coordinator to respond to the MLME-ORPHAN.indication primitive.

The semantics of this primitive are as follows:

```
MLME-ORPHAN.response      (
    OrphanAddress,
    ShortAddress,
    AssociatedMember,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-100.

Table 10-100—MLME-ORPHAN.response parameters

Name	Type	Valid range	Description
OrphanAddress	Extended address	Any valid extended address	The address of the orphaned device.
ShortAddress	Integer	0x0000–0xffff	The short address allocated to the orphaned device if it is associated with this coordinator. The special short address 0xffff indicates that no short address was allocated, and the device will use its extended address in all communications. If the device was not associated with this coordinator, this field will contain the value 0xffff and be ignored on receipt.
AssociatedMember	Boolean	TRUE, FALSE	TRUE if the orphaned device is associated with this coordinator or FALSE otherwise.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

If the AssociatedMember parameter is set to TRUE, the orphaned device is associated with the coordinator. In this case, the MLME generates and sends the Coordinator Realignment command, as defined in 7.5.4, to the orphaned device containing the value of the ShortAddress field. This command is sent in the CAP if the coordinator is on a PAN using superframe structure or immediately otherwise. If the AssociatedMember parameter is set to FALSE, the orphaned device is not associated with the coordinator and this primitive will be ignored. If the orphaned device does not receive the Coordinator Realignment command following its orphan notification within *macResponseWaitTime*, it will assume it is not associated to any coordinator in range.

If the frame was successfully transmitted and an acknowledgment was received, if requested, the MAC sublayer will issue the MLME-COMM-STATUS.indication primitive with a Status of SUCCESS.

10.21 Association and disassociation

10.21.1 Overview of association and disassociation

In some networks the network requires association of the network before a device can properly join the network. This section describes a way for the device to associate/disassociate to/from a coordinator.

10.21.2 Association

The next higher layer will attempt to associate only after having first performed a MAC sublayer reset, by issuing the MLME-RESET.request primitive with the SetDefaultPib set to TRUE, and then having completed either an active or a passive channel scan, as defined in 6.4.1.2. The results of the channel scan would have then been used to choose a suitable PAN. The algorithm for selecting a suitable PAN with which to associate from the list of PAN descriptors returned from the channel scan procedure is outside the scope of this standard.

Following the selection of a PAN with which to associate, the next higher layers will request through the MLME-ASSOCIATE.request primitive, as described in 10.21.6.1.2, that the MLME configures the following PHY and MAC PIB attributes to the values necessary for association:

- *phyCurrentChannelInfo* shall be set equal to the ChannelInfo parameter of the MLME-ASSOCIATE.request primitive.
- *macPanId* shall be set equal to the CoordPanId parameter of the MLME-ASSOCIATE.request primitive.
- *macCoordExtendedAddress* or *macCoordShortAddress*, depending on which is known from the Beacon frame from the coordinator through which it wishes to associate, shall be set equal to the CoordAddress parameter of the MLME-ASSOCIATE.request primitive.

A coordinator shall allow association only if *macAssociationPermit* is set to TRUE. Similarly, a device should attempt to associate only with a PAN through a coordinator that is currently allowing association, as indicated in the results of the scanning procedure. If a coordinator with *macAssociationPermit* set to FALSE receives an Association Request command from a device, the command shall be ignored.

A device that is instructed to associate with a PAN, through the MLME-ASSOCIATE.request primitive, tries to associate only with an existing PAN and will not attempt to start its own PAN.

The MAC sublayer of an unassociated device shall initiate the association procedure by sending an Association Request command, as described in 10.21.5.1, to the coordinator of an existing PAN. If the Association Request command cannot be sent due to a channel access failure, the MAC sublayer shall notify the next higher layer.

The acknowledgment to an Association Request command does not mean that the device has associated. The next higher layer of the coordinator needs time to determine whether the current resources available on the PAN are sufficient to allow another device to associate. The next higher layer should make this decision within *macResponseWaitTime*. If the next higher layer of the coordinator finds that the device was previously associated on its PAN, all previously obtained device-specific information should be replaced. If sufficient resources are available, the next higher layer should allocate a short address to the device that is unique within the PAN, and the MAC sublayer shall generate an Association Response command, as described in 10.21.5.2, containing the new address and a Association Status field indicating a successful association. If sufficient resources are not available, the next higher layer of the coordinator should inform the MAC sublayer, and the MLME shall generate an Association Response command containing a Association Status field indicating a failure, as defined in Table 10-102. The Association Response command shall be sent to the device requesting association using indirect transmission; i.e., the Association Response command shall be added to the list of pending transactions stored on the coordinator and extracted at the discretion of the device concerned using the method described in 10.22.3.

If the Allocate Address field of the Capability Information field, as described in 10.21.5.1, of the Association Request command is set to one, the next higher layer of the coordinator shall allocate an address with a range depending on the addressing mode supported by the coordinator, as described in Table 10-101. If the Allocate Address field of the Association Request command is set to zero, the short address shall be equal to 0xffffe. A short address of 0xffffe is a special case that indicates that the device has associated but has not been allocated a short address by the coordinator. In this case, the device shall use only its extended address to operate on the network.

On receipt of the acknowledgment to the Association Request command, the device shall wait for at most *macResponseWaitTime* for the coordinator to make its association decision; *macResponseWaitTime* is a network-topology-dependent parameter and may be set to match the specific requirements of the network that a device is trying to join. If the device is tracking the beacon, it shall attempt to extract the Association Response command from the coordinator whenever it is indicated in the Beacon frame. If the device is not

tracking the beacon, it shall attempt to extract the Association Response command from the coordinator after *macResponseWaitTime*. If the device does not receive an Association Response command from the coordinator within *macResponseWaitTime*, the MLME shall issue the MLME-ASSOCIATE.confirm primitive, as described in 10.21.6.1.5, with a Status of NO_DATA, and the association attempt shall be deemed a failure. In this case, the next higher layer will terminate any tracking of the beacon. This is achieved by issuing the MLME-SYNC.request primitive, as described in 10.2.10.2, with the TrackBeacon parameter set to FALSE.

If the Association Status field of the Association Response command indicates that the association was successful, the device shall store the address contained in the Short Address field of the command in *macShortAddress*; communication on the PAN using this short address shall depend on its range, as described in Table 10-101. If the original beacon selected for association following a scan contained the short address of the coordinator, the extended address of the coordinator, contained in the MHR of the Association Response command, shall be stored in *macCoordExtendedAddress*.

Table 10-101—Usage of the short address

Value of <i>macShortAddress</i>	Description
0x0000–0xffffd	If a source address is included, the device shall use short source addressing mode for Beacon frames and Data frames and the appropriate source addressing mode specified in 7.3.4 for MAC Command frames.
0xffffe	If a source address is included, the device shall use extended source addressing mode for Beacon frames and Data frames and the appropriate source addressing mode specified in 7.3.4 for MAC Command frames.
0xfffff	The device shall use the appropriate source addressing mode specified in 7.3.4 for MAC commands.

If the value of the Association Status field of the command is not Association successful, if there were a communication failure during the association process due to a missed Ack frame, or if the Association Response command was not received, the device shall set *macPanId* to the default value.

A message sequence chart for association is illustrated in Figure 10-151.

Figure 10-152 illustrates a sequence of messages that may be used by a device that is not tracking the beacon of the coordinator to successfully associate with a PAN.

When an association request is received with the Suspendable CSMA-CA field set to one, and the association is successful, the association status field shall be set to Suspendable CSMA-CA association successful when the responding device will perform backoff suspension as described in 10.12 and shall be set to Association successful otherwise.

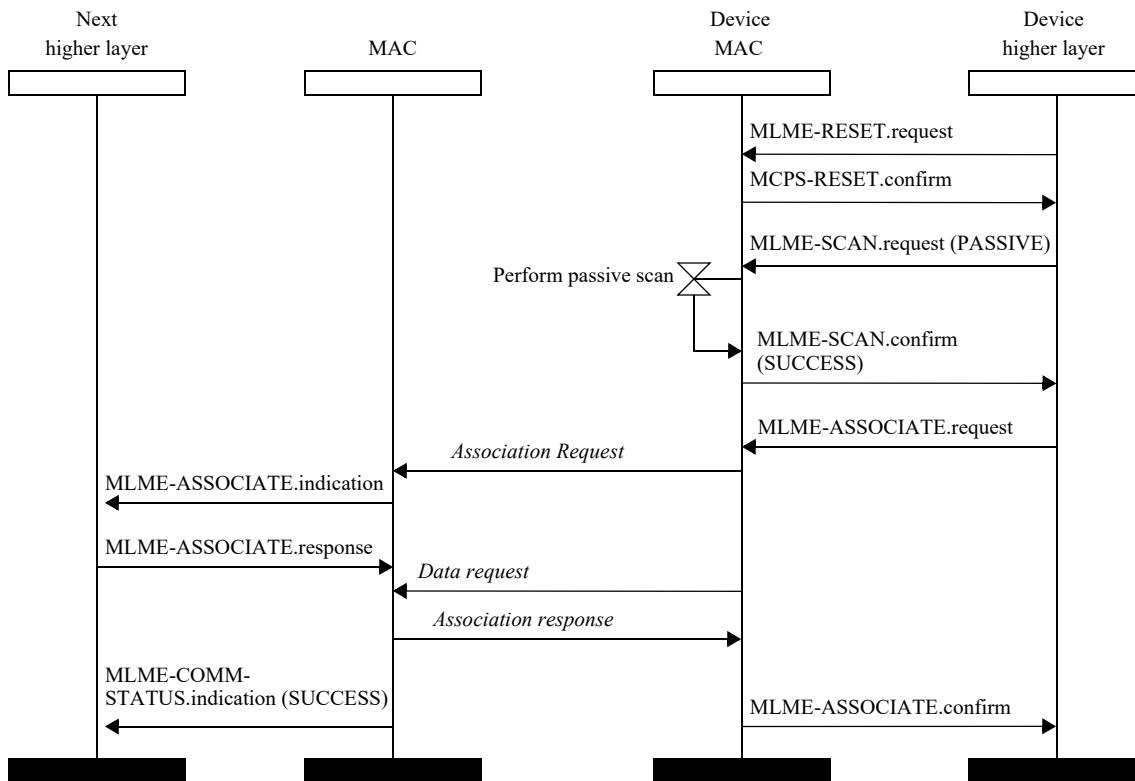


Figure 10-151—Association message sequence chart

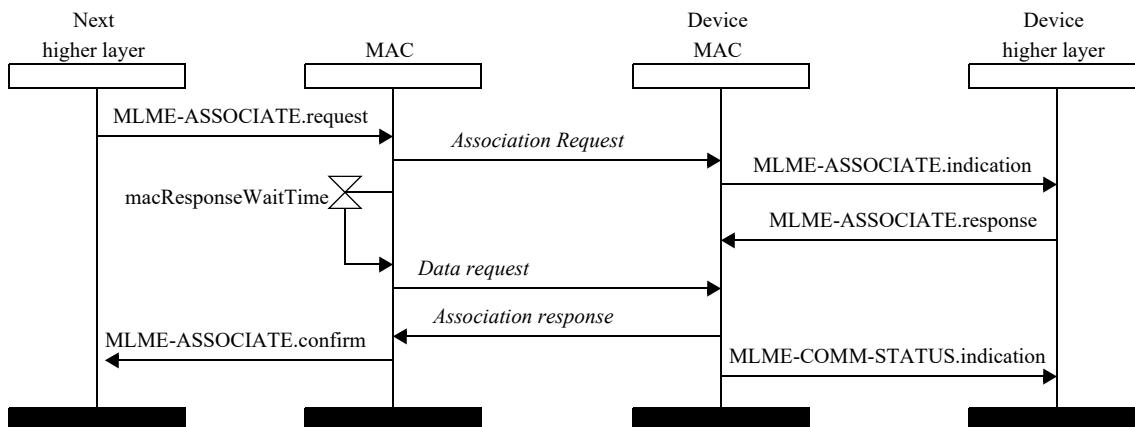


Figure 10-152—Association for a device that is not tracking beacons

10.21.3 Disassociation

The disassociation procedure is initiated by the next higher layer by issuing the MLME-DISASSOCIATE.request primitive, as described in 10.21.6.2.2, to the MLME.

When a coordinator wants one of its associated devices to leave the PAN, the MLME of the coordinator shall send the Disassociation Notification command in the manner specified by the TxIndirect parameter of the MLME-DISASSOCIATE.request primitive previously sent by the next higher layer. If TxIndirect is TRUE, the MLME of the coordinator shall send the Disassociation Notification command to the device using indirect transmission; i.e., the Disassociation Notification command shall be added to the list of pending transactions stored on the coordinator and extracted at the discretion of the device concerned using the method described in 10.22.3. If the command is not successfully extracted by the device, the coordinator should consider the device disassociated. Otherwise, the MLME shall send the Disassociation Notification command to the device directly. In this case, if the Disassociation Notification command cannot be sent due to a channel access failure, the MAC sublayer shall notify the next higher layer.

If the direct or indirect transmission fails, the coordinator should consider the device disassociated.

If an associated device wants to leave the PAN, the MLME of the device shall send a Disassociation Notification command to its coordinator. If the Disassociation Notification command cannot be sent due to a channel access failure, the MAC sublayer shall notify the next higher layer. If an acknowledgment to the Disassociation Notification command is not received, the device should consider itself disassociated.

If the source address contained in the Disassociation Notification command is equal to *macCoordExtendedAddress*, the device should consider itself disassociated. If the command is received by a coordinator and the source is not equal to *macCoordExtendedAddress*, it shall verify that the source address corresponds to one of its associated devices; if so, the coordinator should consider the device disassociated. If none of these conditions are satisfied, the Disassociation Notification command shall be ignored.

An associated device shall disassociate itself by removing all references to the PAN; the MLME shall set *macPanId*, *macShortAddress*, *macAssociatedPanCoord*, *macCoordShortAddress*, and *macCoordExtendedAddress* to the default values. The next higher layer of a coordinator should disassociate a device by removing all references to that device.

The next higher layer of the requesting device shall be notified of the result of the disassociation procedure through the MLME-DISASSOCIATE.confirm primitive, as described in 10.21.6.2.4.

Figure 10-153 illustrates the sequence of messages for a device to disassociate itself from the PAN.

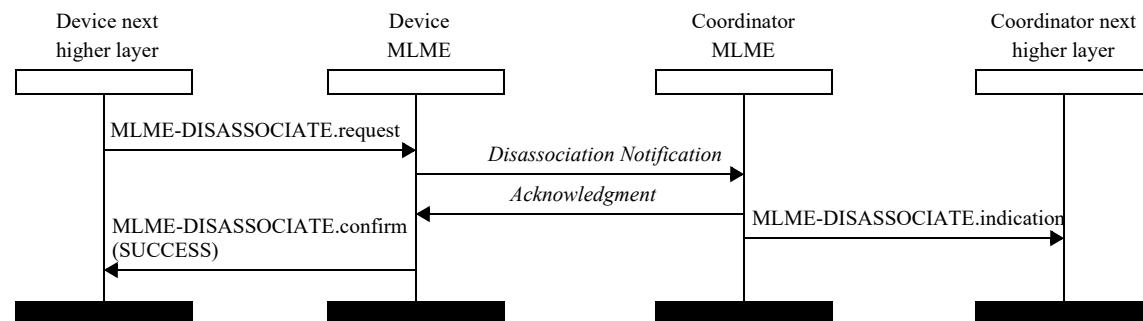


Figure 10-153—Message sequence chart for disassociation initiated by a device

Figure 10-154 illustrates the sequence necessary for a coordinator in a PAN using superframe structure to successfully disassociate a device from its PAN using indirect transmission.

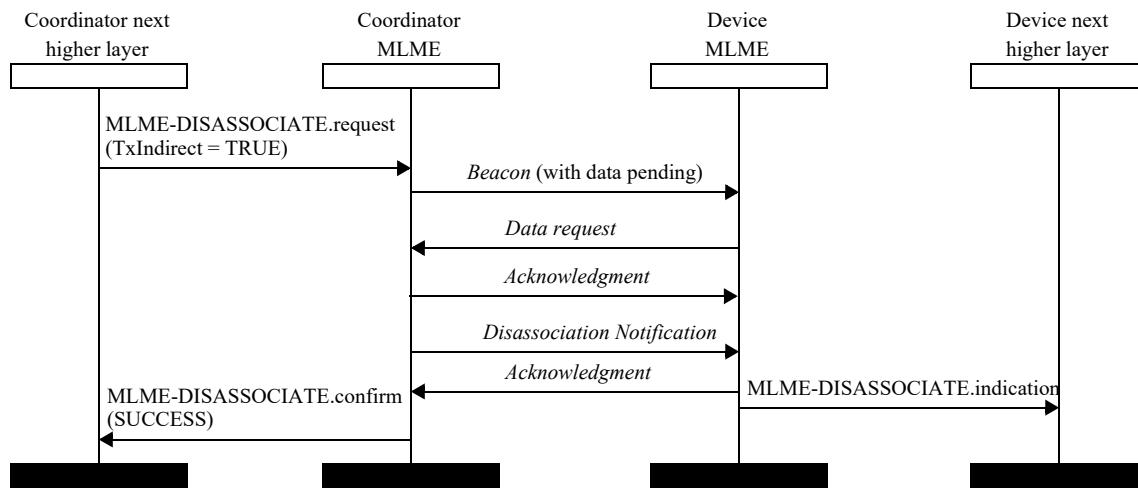


Figure 10-154—Message sequence chart for disassociation initiated by a coordinator, using indirect transmission, in a PAN using superframe structure

10.21.4 Fast association

Fast association is optional.

A device is instructed to fast associate with a PAN through the MLME-ASSOCIATE.request primitive.

The MAC sublayer of an unassociated device initiates the fast association procedure by sending an Association Request command to the coordinator of an existing PAN with the Association Type bit set to one in the Capability Information field.

If the device does not receive an Association Response command from the coordinator within *macResponseWaitTime*, the MLME shall issue the MLME-ASSOCIATE.confirm primitive, as described in 10.21.6.1.5, with a Status of NO_DATA, and the association attempt shall be deemed a failure.

If the coordinator next higher layer accepts the association request, it sends an MLME-ASSOCIATE.response to the MAC sublayer allocating a short address to the device that is unique within the PAN. If the coordinator next higher layer rejects the association request, it will send an MLME-ASSOCIATE.response with a Association Status parameter indicating the reason for the rejection. Upon receipt of an MLME-ASSOCIATE.response primitive, the MAC sublayer shall generate an Association Response command. If the request was successful, the Association Response command contains the new address and a Association Status field indicating a successful fast association. If the request failed, the Association Response command contains the Association Status field set to indicate the reason the request failed.

If the Association Type field of the Capability Information field of the Association Request command is set to one, the MAC sublayer of the coordinator shall send the Association Response command to the device directly. If the Association Type field of the Capability Information field of the Association Request command is set to zero, the Association Response command shall be sent as in 10.3.4.1.

If the Association Status field of the command indicates Fast association successful, the device shall store the address contained in the Short Address field of the command in *macShortAddress* for its communication use in the PAN.

Figure 10-155 illustrates a sequence of messages for fast association.

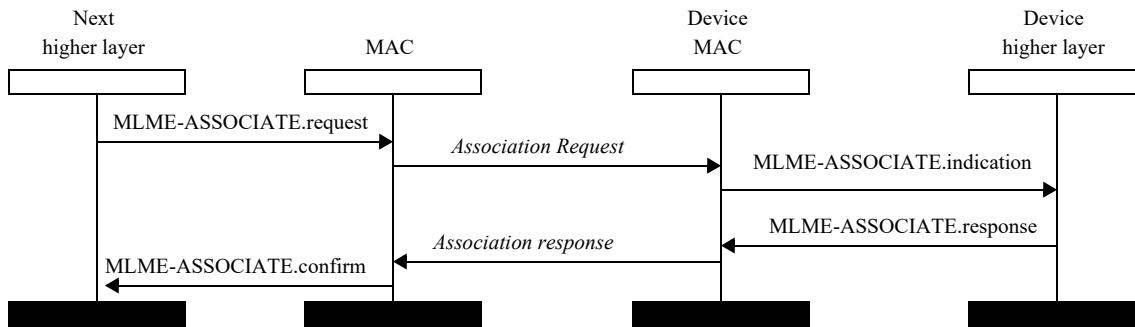


Figure 10-155—Fast Association message sequence chart

10.21.5 MAC commands for association and disassociation

10.21.5.1 Association Request command

This command shall only be sent by an unassociated device that wishes to associate with a PAN. A device shall only associate with a PAN through the PAN coordinator or a coordinator allowing association, as determined through the scan procedure.

The Source Addressing Mode field shall be set to indicate extended addressing. The Destination Addressing Mode field shall be set to the same mode as indicated in the Beacon frame to which the Association Request command refers.

The Frame Pending field shall be set to zero and ignored upon reception, and the AR field shall be set to one.

The Destination PAN ID field shall contain the identifier of the PAN to which to associate. The Destination Address field shall contain the address from the Beacon frame that was transmitted by the coordinator to which the Association Request command is being sent. If the Version field is set to 0b10, the Source PAN ID field is omitted. Otherwise, the Source PAN ID field shall contain the broadcast PAN ID. The Source Address field shall contain the value of *macExtendedAddress*.

The Association Request command Content field shall be formatted as illustrated in Figure 10-156.

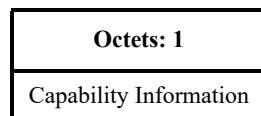


Figure 10-156—Association Request command Content field format

The Capability Information field shall be formatted as illustrated in Figure 10-157.

Bits: 0	1	2	3	4	5	6	7
Reserved	Device Type	Power Source	Receiver On When Idle	Association Type	Suspendable CSMA-CA	Security Capability	Allocate Address

Figure 10-157—Capability Information field format

The Device Type field should be set to one.

The Power Source field shall be set to one if the device is receiving power from the alternating current mains. Otherwise, the Power Source field shall be set to zero.

The Receiver On When Idle field shall be set to one if the device does not disable its receiver to conserve power during idle periods. Otherwise, the Receiver On When Idle field shall be set to zero.

The Association Type field shall be set to one if the device requests fast association and zero otherwise.

The Suspendable CSMA-CA field shall be set to one to indicate that the device will perform backoff suspension as described in 10.12 and shall be set to zero otherwise.

The Security Capability field shall be set to one if the device is capable of sending and receiving cryptographically protected MAC frames as specified in 9.2; it shall be set to zero otherwise.

The Allocate Address field shall be set to one if the device wishes the coordinator to allocate a short address as a result of the association procedure. Otherwise, it shall be set to zero.

10.21.5.2 Association Response command

This command shall only be sent by the PAN coordinator or coordinator to a device that is currently trying to associate.

The Destination Addressing Mode and Source Addressing Mode fields shall each be set to indicate extended addressing.

The Frame Pending field shall be set to zero and ignored upon reception, and the AR field shall be set to one.

The Destination PAN ID field shall contain the value of *macPanId*, while the Source PAN ID field shall be omitted. The Destination Address field shall contain the extended address of the device requesting association. The Source Address field shall contain the value of *macExtendedAddress*. The PAN ID Compression field shall be set as specified in 7.2.2.6.

The Association Response command Content field shall be formatted as illustrated in Figure 10-158.

Octets: 2	1
Short Address	Association Status

Figure 10-158—Association Response command Content field format

If the coordinator was not able to associate the device to its PAN, the Short Address field shall be set to 0xffff, and the Association Status field shall contain the reason for the failure. If the coordinator was able to associate the device to its PAN, this field shall contain the short address that the device may use in its communications on the PAN until it is disassociated.

A Short Address field value equal to 0xfffe shall indicate that the device has been successfully associated with a PAN but has not been allocated a short address. In this case, the device shall communicate on the PAN using only its extended address.

Valid values of the Association Status field are defined in Table 10-102.

Table 10-102—Valid values of the Association Status field

Association status	Description
0x00	Association successful.
0x01	PAN at capacity.
0x02	PAN access denied.
0x03	Hopping sequence offset duplication.
0x04–0x7f	Reserved.
0x80	Fast association successful.
0x81	Suspendable CSMA-CA association successful.
0x81–0xff	Reserved.

10.21.5.3 Disassociation Notification command

The PAN coordinator, a coordinator, or an associated device may send the Disassociate Notification command.

The Destination Addressing Mode field shall be set according to the addressing mode specified by the corresponding primitive. The Source Addressing Mode field shall be set to indicate extended addressing.

The Frame Pending field shall be set to zero and ignored upon reception, and the AR field shall be set to one.

The Destination PAN ID field shall contain the value of *macPanId*. The Source PAN ID field shall be omitted. If the coordinator is disassociating a device from the PAN, then the Destination Address field shall contain the address of the device being removed from the PAN. If an associated device is disassociating from the PAN, then the Destination Address field shall contain the value of either *macCoordShortAddress*, if the Destination Addressing Mode field is set to indicate short addressing, or *macCoordExtendedAddress*, if the Destination Addressing Mode field is set to indicate extended addressing. The Source Address field shall contain the value of *macExtendedAddress*. The PAN ID Compression field shall be set as specified in 7.2.2.6.

The Disassociation Notification command Content field shall be formatted as illustrated in Figure 10-159.

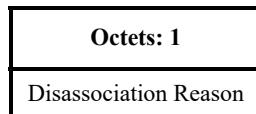


Figure 10-159—Disassociation Notification command Content field format

Valid values of the Disassociation Reason field are defined in Table 10-103.

Table 10-103—Valid Disassociation Reason codes

Disassociate reason	Description
0x00	Reserved.
0x01	The coordinator wishes the device to leave the PAN.
0x02	The device wishes to leave the PAN.
0x03–0xff	Reserved.

10.21.6 MAC management service primitives for association and disassociation

10.21.6.1 Association primitives

10.21.6.1.1 General

These primitives are used when a device becomes associated with a PAN.

10.21.6.1.2 MLME-ASSOCIATE.request

The MLME-ASSOCIATE.request primitive is used by a device to request an association with a coordinator.

The semantics of this primitive are as follows:

```

MLME-ASSOCIATE.request      (
    ChannelInfo,
    CoordAddrMode,
    CoordPanId,
    CoordAddress,
    CapabilityInformation,
    SecurityParams,
    ChannelOffset,
    HoppingSequenceld,
    DsmeAssociation,
    Direction,
    AllocationOrder,
    HoppingSequenceRequest
)
    
```

The primitive parameters are defined in Table 10-104.

Table 10-104—MLME-ASSOCIATE.request parameters

Name	Type	Valid range	Description
ChannelInfo	Channel information structure as defined in 11.1.3.1	Any valid channel	The channel on which to attempt association.
CoordAddrMode	Enumeration	SHORT, EXTENDED	The coordinator addressing mode for this primitive and subsequent MPDU.
CoordPanId	Integer	0x0000–0xffff	The identifier of the PAN with which to associate.
CoordAddress	Short address or extended address	As specified by the CoordAddrMode parameter	The address of the coordinator with which to associate.
CapabilityInformation	Bitmap	As defined in 10.21.5.1	Specifies the operational capabilities of the associating device.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.
ChannelOffset	Integer	0x00–0xffff	Specifies the offset value of Hopping Sequence.
HoppingSequenceId	Integer	0x00–0x0f	Indicate the ID of channel hopping sequence in use: 0x00: a default hopping sequence 0x01: a hopping sequence generated by PAN coordinator 0x02–0x0f: a hopping sequence set by the next higher layer If a coordinator receives an Association Request command with HoppingSequenceId of 1, it replies with a channel hopping sequence in an association response command.
DsmeAssociation	Boolean	TRUE, FALSE	Set to TRUE if the device is requesting GTS allocation during association, FALSE otherwise.
Direction	Enumeration	TX, RX	As defined in Table 10-25.
AllocationOrder	Integer	0x00–0x08	As defined in 10.4.12.2.
HoppingSequenceRequest	Boolean	TRUE, FALSE	Indicates whether a hopping sequence is requested. A value of FALSE indicates that a hopping sequence is not requested. A value of TRUE indicates that a hopping sequence is requested.

On receipt of the MLME-ASSOCIATE.request primitive, the MLME of an unassociated device first updates the appropriate PHY and MAC PIB attributes, as described in 10.21.2, and if DsmeAssociation is FALSE, then it then generates an Association Request command, as defined in 10.21.5.1. If DsmeAssociation is TRUE, then generates an DSME Association Request command, as defined in 10.4.12.1.

The SecurityParams parameter specifies the level of security to be applied to the Association Request command. Typically, the Association Request command should not be implemented using security. However, if the device requesting association shares a key with the coordinator, then security may be specified.

10.21.6.1.3 MLME-ASSOCIATE.indication

The MLME-ASSOCIATE.indication primitive is used to indicate the reception of an Association Request command specified in 10.21.5.1 or DSME Association Request command as specified in 10.4.12.1.

The semantics of this primitive are as follows:

```
MLME-ASSOCIATE.indication ( 
    DeviceAddress,
    CapabilityInformation,
    SecurityParams,
    ChannelOffset,
    HoppingSequenceId,
    DsmeAssociation,
    Direction,
    AllocationOrder,
    HoppingSequenceRequest
)
```

The primitive parameters are defined in Table 10-105.

Table 10-105—MLME-ASSOCIATE.indication parameters

Name	Type	Valid range	Description
DeviceAddress	Extended address	An extended address	The address of the device requesting association.
CapabilityInformation	Bitmap	As defined in 10.21.5.1	The operational capabilities of the device requesting association.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.
ChannelOffset	Integer	0x0000–0xffff	Specifies the offset value of Hopping Sequence.
HoppingSequenceId	Integer	0x00–0x0f	Indicates the ID of channel hopping sequence in use: 0x00: the default hopping sequence 0x01: a hopping sequence generated by PAN coordinator 0x02–0x0f: a hopping sequence set by the next higher layer If a coordinator receives an Association Request command with HoppingSequenceId of 0x01, it replies with a channel hopping sequence in an association response command.
DsmeAssociation	Boolean	TRUE, FALSE	Set to TRUE if the device is requesting GTS allocation during association, FALSE otherwise.

Table 10-105—MLME-ASSOCIATE.indication parameters (continued)

Name	Type	Valid range	Description
Direction	Enumeration	TX, RX	As defined in Table 10-25.
AllocationOrder	Integer	0x00–0x08	As defined in 10.4.12.2.
HoppingSequenceRequest	Boolean	TRUE, FALSE	Indicates whether a hopping sequence is requested. A value of FALSE indicates that a hopping sequence is not requested. A value of TRUE indicates that a hopping sequence is requested.

When the next higher layer of a coordinator receives the MLME-ASSOCIATE.indication primitive, the coordinator determines whether to accept or reject the unassociated device using an algorithm outside the scope of this standard.

10.21.6.1.4 MLME-ASSOCIATE.response

The MLME-ASSOCIATE.response primitive is used to initiate a response to an MLME-ASSOCIATE.indication primitive.

The semantics of this primitive are as follows:

```
MLME-ASSOCIATE.response (DeviceAddress,
                           AssocShortAddress,
                           SecurityParams,
                           ChannelOffset,
                           HoppingSequence,
                           DsmeAssociation,
                           AllocationOrder,
                           BilIndex,
                           SuperframeId,
                           SlotId,
                           ChannelIndex,
                           AssociationStatus)
```

The primitive parameters are defined in Table 10-106.

Table 10-106—MLME-ASSOCIATE.response parameters

Name	Type	Valid range	Description
DeviceAddress	Extended address	Any valid extended address	The address of the device requesting association.
AssocShortAddress	Integer	0x0000–0xffff	The short address allocated by the coordinator on successful association. This parameter is set to 0xffff if the association was unsuccessful.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

Table 10-106—MLME-ASSOCIATE.response parameters (continued)

Name	Type	Valid range	Description
ChannelOffset	Integer	0x0000–0xffff	Specifies the offset value of Hopping Sequence.
HoppingSequence	Set of octets	—	For TSCH, specifies the sequence of channel numbers that is set by a higher layer as described in 10.16. For DSME, as defined in 10.4.12.2.
DsmeAssociation	Boolean	TRUE, FALSE	Set to TRUE if the device is requesting GTS allocation during association, FALSE otherwise.
AllocationOrder	Integer	0x00–0x08	As defined in 10.4.12.2.
BiIndex	Integer	0x00–0xff	As defined in 10.4.12.2.
SuperframeId	Integer	0x0000–0xffff	As defined in 10.4.12.2.
SlotId	Integer	0x00–0x0e	As defined in 10.4.12.2.
ChannelIndex	Integer	0x00–0x1f	As defined in 10.4.12.2.
AssociationStatus	Enumeration	As defined in Table 10-102	The association status of the association attempt as defined in 10.21.5.2.

If DsmeAssociation parameter is FALSE and when the MLME of a coordinator receives the MLME-ASSOCIATE.response primitive, it generates an Association Response command, as described in 10.21.5.2, and attempts to send it to the device requesting association, as described in 10.21.2. If the DsmeAssociation parameter is TRUE and when the MLME of a coordinator receives the MLME-ASSOCIATE.response primitive, it generates an DSME Association Response command, as described in 10.4.12.2, and attempts to send it to the device requesting association, as described in 10.21.2.

If the AssociationStatus field of MLME-ASSOCIATE.response primitive is set to Fast association successful, the association response command shall be sent to the device requesting fast association directly.

10.21.6.1.5 MLME-ASSOCIATE.confirm

The MLME-ASSOCIATE.confirm primitive is used to inform the next higher layer of the initiating device whether its request to associate was successful or unsuccessful.

The semantics of this primitive are as follows:

```
MLME-ASSOCIATE.confirm      (
    AssocShortAddress,
    AssociationStatus,
    SecurityParams,
    ChannelOffset,
    HoppingSequence,
    DsmeAssociation,
    AllocationOrder,
    BiIndex,
    SuperframeId,
    SlotId,
    ChannelIndex,
    Status
)
```

The primitive parameters are defined in Table 10-107.

Table 10-107—MLME-ASSOCIATE.confirm parameters

Name	Type	Valid range	Description
AssocShortAddress	Integer	0x0000–0xffff	The short address allocated by the coordinator on successful association. This parameter will be equal to 0xffff if the association attempt was unsuccessful.
AssociationStatus	Enumeration	As defined in Table 10-102	The association status of the association attempt from association request command as defined in 10.21.5.2.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.
ChannelOffset	Integer	0x0000–0xffff	Specifies the offset value of Hopping Sequence.
Hopping Sequence	Set of octets	—	As defined in Table 10-106.
DsmeAssociation	Boolean	TRUE, FALSE	Set to TRUE if the device is requesting GTS allocation during association, FALSE otherwise.
AllocationOrder	Integer	0x00–0x08	As defined in 10.4.12.2.
BiIndex	Integer	0x00–0xff	As defined in 10.4.12.2.
SuperframeId	Integer	0x0000–0xffff	As defined in 10.4.12.2.
SlotId	Integer	0x00–0x0e	As defined in 10.4.12.2.
ChannelIndex	Integer	0x00–0x1f	As defined in 10.4.12.2.
Status	Enumeration	SUCCESS, NO_DATA, also see 8.2.2	The status of the association attempt.

If the association request was successful, then the Status parameter will be set to SUCCESS, and the AssociationStatus parameter will indicate status of the association.

10.21.6.2 Disassociation primitives

10.21.6.2.1 General

These primitives are used by a device to disassociate from a PAN or by the coordinator to disassociate a device from a PAN.

10.21.6.2.2 MLME-DISASSOCIATE.request

The MLME-DISASSOCIATE.request primitive is used by an associated device to notify the coordinator of its intent to leave the PAN. It is also used by the coordinator to instruct an associated device to leave the PAN.

The semantics of this primitive are as follows:

```
MLME-DISASSOCIATE.request      (
    DeviceAddrMode,
    DevicePanId,
    DeviceAddress,
    DisassociateReason,
    TxIndirect,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-108.

Table 10-108—MLME-DISASSOCIATE.request parameters

Name	Type	Valid range	Description
DeviceAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the device to which to send the Disassociation Notification command.
DevicePanId	Integer	0x0000–0xffff	The PAN ID of the device to which to send the Disassociation Notification command.
DeviceAddress	Short address or extended address	As specified by the DeviceAddrMode parameter	The address of the device to which to send the Disassociation Notification command.
DisassociateReason	Integer	0x00–0xff	The reason for the disassociation, as described in 10.21.5.3.
TxIndirect	Boolean	TRUE, FALSE	TRUE if the Disassociation Notification command is to be sent indirectly.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

If the DeviceAddrMode parameter is equal to SHORT and the DeviceAddress parameter is equal to *macCoordShortAddress* or if the DeviceAddrMode parameter is equal to EXTENDED and the DeviceAddress parameter is equal to *macCoordExtendedAddress*, the TxIndirect parameter is ignored, and the MLME sends a Disassociation Notification command, as defined in 10.21.5.3, to its coordinator in the CAP for a PAN using superframe structure or immediately for a PAN not using superframe structure.

If the DeviceAddrMode parameter is equal to SHORT and the DeviceAddress parameter is not equal to *macCoordShortAddress* or if the DeviceAddrMode parameter is equal to EXTENDED and the DeviceAddress parameter is not equal to *macCoordExtendedAddress*, and if this primitive was received by the MLME of a coordinator with the TxIndirect parameter set to TRUE, the Disassociation Notification command will be sent using indirect transmission, as described in 10.22.2.

If the DeviceAddrMode parameter is equal to SHORT and the DeviceAddress parameter is not equal to *macCoordShortAddress* or if the DeviceAddrMode parameter is equal to EXTENDED and the DeviceAddress parameter is not equal to *macCoordExtendedAddress*, and if this primitive was received by the MLME of a coordinator with the TxIndirect parameter set to FALSE, the MLME sends a Disassociation Notification command to the device in the CAP for a PAN using superframe structure or immediately for a PAN not using superframe structure.

10.21.6.2.3 MLME-DISASSOCIATE.indication

The MLME-DISASSOCIATE.indication primitive is used to indicate the reception of a Disassociation Notification command.

The semantics of this primitive are as follows:

```
MLME-DISASSOCIATE.indication ( 
    DeviceAddress,
    DisassociateReason,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-109.

Table 10-109—MLME-DISASSOCIATE.indication parameters

Name	Type	Valid range	Description
DeviceAddress	Extended address	Any valid extended address	The address of the device requesting disassociation.
DisassociateReason	Integer	0x00–0xff	The reason for the disassociation, as defined in 10.21.5.3.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

10.21.6.2.4 MLME-DISASSOCIATE.confirm

The MLME-DISASSOCIATE.confirm primitive reports the results of an MLME-DISASSOCIATE.request primitive.

The semantics of this primitive are as follows:

```
MLME-DISASSOCIATE.confirm      (
    DeviceAddrMode,
    DevicePanId,
    DeviceAddress,
    Status
)
```

The primitive parameters are defined in Table 10-110.

Table 10-110—MLME-DISASSOCIATE.confirm parameters

Name	Type	Valid range	Description
DeviceAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the device that has either requested disassociation or been instructed to disassociate by its coordinator.
DevicePanId	Integer	0x0000–0xffff	The PAN ID of the device that has either requested disassociation or been instructed to disassociate by its coordinator.
DeviceAddress	Short address or extended address	As specified by the DeviceAddrMode parameter	The address of the device that has either requested disassociation or been instructed to disassociate by its coordinator.
Status	Enumeration	SUCCESS, also see 8.2.2	The status of the disassociation attempt.

This primitive returns a Status of either SUCCESS, indicating that the Disassociation Notification was successful, or the appropriate Status parameter value indicating the reason for failure.

If the DevicePanId parameter is not equal to *macPanId* in the MLME-DISASSOCIATE.request primitive, the Status parameter shall be set to INVALID_PARAMETER.

10.21.7 MAC constants and PIB attributes for association and disassociation

Association and disassociation attributes are described in Table 10-111.

Table 10-111—Association and disassociation related PIB attributes

Attribute	Type	Range	Description	Default
<i>macAssociatedPanCoord</i>	Boolean	TRUE, FALSE	Indication of whether the device is associated to the PAN through the PAN coordinator. A value of TRUE indicates the device has associated through the PAN coordinator. Otherwise, the value is set to FALSE.	FALSE
<i>macAssociationPermit*</i>	Boolean	TRUE, FALSE	Indication of whether a coordinator is currently allowing association. A value of TRUE indicates that association is permitted.	FALSE

10.22 Extracting pending data from a coordinator

10.22.1 Overview

A device is instructed to poll the coordinator when the MLME receives the MLME-POLL.request primitive, as described in 10.22.5.2. On receipt of this primitive, the MLME shall follow the procedure for extracting pending data from the coordinator as described in this subclause.

10.22.2 Transaction handling

Because this standard favors very low cost devices that, in general, will be battery powered, transactions can be instigated from the devices themselves rather than from the coordinator. In other words, either the coordinator needs to indicate in its beacon when messages are pending for devices or the devices themselves need to poll the coordinator to determine whether they have any messages pending. Such transfers are called *indirect transmissions*.

The coordinator shall begin handling a transaction on receipt of an indirect transmission request either via the MCPS-DATA.request primitive or via a request from the MLME to send a MAC command instigated by a primitive from the next higher layer, such as the MLME-ASSOCIATE.response primitive, as described in 10.21.6.1.4. On completion of the transaction, the MAC sublayer shall indicate a Status value to the next higher layer. If a request primitive instigated the indirect transmission, the corresponding confirm primitive shall be used to convey the appropriate Status value. Conversely, if a response primitive instigated the indirect transmission, the MLME-COMM-STATUS.indication primitive shall be used to convey the appropriate Status value. The MLME-COMM-STATUS.indication primitive can be related to its corresponding response primitive by examining the Destination Address field.

The information contained in the indirect transmission request forms a transaction, and the device shall be capable of storing at least one transaction. On receipt of an indirect transmission request, if there is no capacity to store another transaction, the MAC sublayer shall indicate to the next higher layer a Status of TRANSACTION_OVERFLOW in the appropriate corresponding primitive.

If the coordinator is capable of storing more than one transaction, it shall transmit transactions for the same device in the order in which they arrived at the MAC sublayer. For each transaction sent, if another exists for the same device, the MAC sublayer shall set its Frame Pending field to one, indicating the additional pending data.

Each transaction shall persist in the coordinator for at most *macTransactionPersistenceTime*. If the transaction is not successfully extracted by the appropriate device within this time, the transaction

information shall be discarded and the MAC sublayer shall indicate to the next higher layer a Status of TRANSACTION_EXPIRED in the appropriate corresponding primitive. In order to be successfully extracted, an acknowledgment shall be received if one was requested.

If the transaction was successful, the transaction information shall be discarded, and the MAC sublayer shall indicate to the next higher layer a Status of SUCCESS in the appropriate corresponding primitive.

If the coordinator transmits beacons, it shall list the addresses of the devices to which each transaction is associated in the Address List field and indicate the number of addresses in the Pending Address Specification field of the Beacon frame. If the coordinator is able to store more than seven pending transactions, it shall indicate them in its beacon on a first-come-first-served basis, ensuring that the Beacon frame contains at most seven addresses. For transactions requiring a GTS, the PAN coordinator shall not add the address of the recipient to its set of pending addresses in the Beacon frame. Instead it shall transmit the transaction in the GTS allocated for the device, as described in 10.25.4.

If there is a transaction pending for the broadcast address, the Frame Pending field in the Beacon frame shall be set to one, and the pending message shall be transmitted immediately following the Beacon frame using the CSMA-CA algorithm. In a PAN using superframe structure, if there is a second message pending for the broadcast address, its transmission shall be delayed until the following superframe.

If a device receives a Beacon frame with the Frame Pending field set to one, it shall leave its receiver enabled to receive the broadcast Data frame from the coordinator.

In a PAN not using superframe structure, upon receipt of the MLME-POLL.request primitive, a device shall attempt to extract the data from the coordinator, as defined in 10.22.

In a PAN using superframe structure, a device that receives a Beacon frame containing its address in the set of pending addresses shall attempt to extract the data from the coordinator.

10.22.3 Extracting pending data from a coordinator

A device on a PAN using superframe structure can determine whether any frames are pending for it by examining the contents of the received Beacon frame, as described in 10.2.6. If the address of the device is contained in the Address List field of the Beacon frame and *macAutoRequest* is TRUE, the MLME of the device shall send a Data Request command, as described in 10.22.4.1, to the coordinator during the CAP with the AR field set to request an acknowledgment; the only exception to this is if the Beacon frame is received while performing an active or passive scan, as described in 6.4.1. There are two other cases for which the MLME shall send a Data Request command to the coordinator. The first case is when the MLME receives the MLME-POLL.request primitive. In the second case, a device may send a Data Request command *macResponseWaitTime* after the acknowledgment to a MAC command, such as during the association procedure. If the data request is intended for the PAN coordinator, the destination address information may be omitted.

If the Data Request command originated from an MLME-POLL.request primitive, the MLME shall perform the security process on the Data Request command based on the SecurityParams parameter of the MLME-POLL.request primitive, according to 9.2.2. Otherwise, the MLME shall perform the security process on the Data Request command based on the *secAutoRequestSecurityParams* according to 9.2.2.

On successfully receiving a Data Request command, the coordinator shall send an Acknowledgment frame, thus confirming its receipt. If the coordinator has enough time to determine whether the device has a frame pending before sending the Ack frame, as described in 10.3.7.1, it shall set the Frame Pending field of the Ack frame accordingly to indicate whether a frame is actually pending for the device. If this is not possible, the coordinator shall set the Frame Pending field of the Ack frame to one.

On receipt of the Ack frame with the Frame Pending field set to zero, the device shall conclude that there are no data pending at the coordinator.

On receipt of the Ack frame with the Frame Pending field set to one, a device shall enable its receiver to receive the corresponding Data frame from the coordinator. If there is an actual Data frame pending within the coordinator for the requesting device, the coordinator shall send the frame to the device using one of the mechanisms described in this subclause. If there is no Data frame pending for the requesting device, the coordinator shall send a Data frame without requesting acknowledgment to the device containing a zero-length payload, indicating that no data are present, using one of the mechanisms described in this subclause.

The Data frame following the acknowledgment of the Data Request command shall be transmitted using one of the following mechanisms:

- Without using CSMA-CA, if the MAC sublayer can commence transmission of the Data frame between $macSifsPeriod$ and $(macSifsPeriod + macUnitBackoffPeriod)$, on a backoff period boundary, and there is time remaining in the CAP for the message, appropriate IFS, and acknowledgment. If a requested Ack frame is not received following this Data frame, the process shall begin anew following the receipt of a new Data Request command.
- Using CSMA-CA, otherwise.

If the requesting device does not receive a Data frame from the coordinator within the expected time or if the requesting device receives a Data frame from the coordinator with a zero-length payload, it shall conclude that there are no data pending at the coordinator. If the requesting device does receive a Data frame from the coordinator, it shall send an Ack frame, if requested, thus confirming receipt.

If the Frame Pending field of the Data frame received from the coordinator is set to one, the device still has more data pending with the coordinator. In this case it may extract the data by sending a new Data Request command to the coordinator.

In Figure 10-160 a poll request is issued to the MLME, which then sends a Data Request command to the coordinator. The corresponding Ack frame has the Frame Pending (FP) field set to zero and the MLME issues the poll request confirmation immediately.

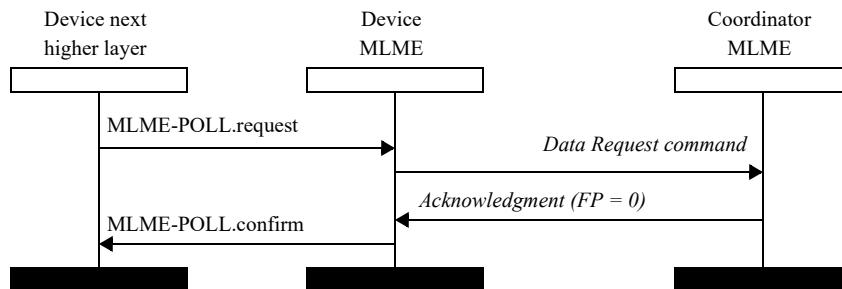


Figure 10-160—Message sequence chart for requesting data from the coordinator when the coordinator does not have data pending

In Figure 10-161 a poll request is issued to the MLME, which then sends a Data Request command to the coordinator. The corresponding Ack frame has the Frame Pending field set to one and the MLME enables the receiver in anticipation of the Data frame from the coordinator. On receipt of this Data frame, the MLME issues a poll request confirmation followed by a data indication containing the data of the received frame.

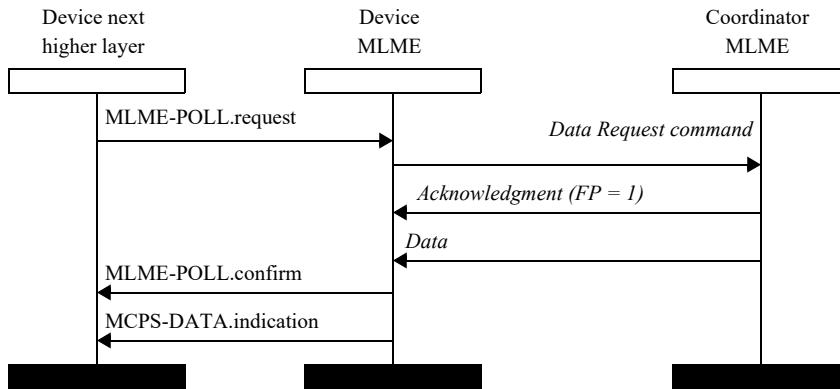


Figure 10-161—Message sequence chart for requesting data from the coordinator when the coordinator has data pending

10.22.4 MAC commands for extracting pending data from a coordinator

10.22.4.1 Data Request command

There are three cases for which this command is sent. On a PAN using superframe structure, this command shall be sent by a device when *macAutoRequest* is equal to TRUE and a Beacon frame indicating that data are pending for that device is received from its coordinator. The coordinator indicates pending data in its Beacon frame by adding the address of the recipient of the data to the Address List field. This command shall also be sent when instructed to do so by the next higher layer on reception of the MLME-POLL.request primitive. In addition, a device may send this command to the coordinator *macResponseWaitTime* after the acknowledgment to an Association Request command.

The Data Request command has a zero-length Content field.

If the Data Request command is being sent in response to the receipt of a Beacon frame indicating that data are pending for that device, the Destination Addressing Mode field may be set to indicate that destination addressing information is not present if the Beacon frame indicated in its Superframe Specification field, as defined in 7.3.1.4; that it originated from the PAN coordinator, as defined in 7.2.2.9; or set otherwise according to the coordinator to which the Data Request command is directed. If the destination addressing information is to be included, the Destination Addressing Mode field shall be set according to the value of *macCoordShortAddress*. If *macCoordShortAddress* is equal to 0xffff, the Destination Addressing Mode field shall be set to indicate extended addressing, and the Destination Address field shall contain the value of *macCoordExtendedAddress*. Otherwise, the Destination Addressing Mode field shall be set to indicate short addressing, and the Destination Address field shall contain the value of *macCoordShortAddress*.

If the Data Request command is being sent in response to the receipt of a Beacon frame indicating that data are pending for that device, the Source Addressing Mode field shall be set according to the addressing mode used for the pending address. If the Source Addressing Mode field is set to indicate short addressing, the Source Address field shall contain the value of *macShortAddress*. Otherwise, the Source Addressing Mode field shall be set to indicate extended addressing and the Source Address field shall contain the value of *macExtendedAddress*.

If the Data Request command is triggered by the reception of an MLME-POLL.request primitive from the next higher layer, then the destination addressing information shall be the same as that contained in the primitive. The Source Addressing Mode field shall be set according to the value of *macShortAddress*. If

macShortAddress is less than 0xffffe, short addressing shall be used. Extended addressing shall be used otherwise.

If the Data Request command is being sent following the acknowledgment to an Association Request command, the Destination Addressing Mode field shall be set according to the coordinator to which the Data Request command is directed. If *macCoordShortAddress* is equal to 0xffffe, extended addressing shall be used. Short addressing shall be used otherwise. The Source Addressing Mode field shall be set to use extended addressing.

If the Destination Addressing Mode field is set to indicate that destination addressing information is not present, the source PAN ID shall contain the value of *macPanId*. Otherwise, the Destination PAN ID field shall contain the value of *macPanId*, while the Source PAN ID field shall be omitted. The PAN ID Compression field shall be set as specified in 7.2.2.6.

The Frame Pending field shall be set to zero and ignored upon reception, and the AR field shall be set to one.

10.22.5 MAC management service primitives for extracting pending data from a coordinator

10.22.5.1 General

These primitives are used to request data from a coordinator.

10.22.5.2 MLME-POLL.request

The MLME-POLL.request primitive prompts the device to request data from the coordinator.

The semantics of this primitive are as follows:

```
MLME-POLL.request ( 
    CoordAddrMode,
    CoordPanId,
    CoordAddress,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-112.

Table 10-112—MLME-POLL.request parameters

Name	Type	Valid range	Description
CoordAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the coordinator to which the poll is intended.
CoordPanId	Integer	0x0000–0xffffe	The PAN ID of the coordinator to which the poll is intended.
CoordAddress	—	As specified by the CoordAddrMode parameter	The address of the coordinator to which the poll is intended.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

On receipt of the MLME-POLL.request primitive, the MLME requests data from the coordinator, as described in 10.22. If the poll is directed to the PAN coordinator, the Data Request command may be

generated without any destination address information present. Otherwise, the Data Request command is always generated with the destination address information in the CoordPanId and CoordAddress parameters.

10.22.5.3 MLME-POLL.confirm

The MLME-POLL.confirm primitive reports the results of a request to poll the coordinator for data.

The semantics of this primitive are as follows:

```
MLME-POLL.confirm      (
    Status
)
```

The primitive parameters are defined in Table 10-113.

Table 10-113—MLME-POLL.confirm parameters

Name	Type	Valid range	Description
Status	Integer	SUCCESS, NO_DATA, also see 8.2.2	The status of the data request.

The MLME-POLL.confirm primitive is generated by the MLME and issued to its next higher layer in response to an MLME-POLL.request primitive. If the request was successful, the Status parameter will be equal to SUCCESS, indicating a successful poll for data. Otherwise, the Status parameter indicates the appropriate error code. The Status values are fully described in 10.22.5.2.

If the Frame Pending field of the Ack frame is set to zero, the MLME will issue the MLME-POLL.confirm primitive with a Status of NO_DATA.

If a frame is received from the coordinator with a zero-length payload or if the frame is a MAC command, the MLME will issue the MLME-POLL.confirm primitive with a Status of NO_DATA. If a frame is received from the coordinator with nonzero-length payload, the MLME will issue the MLME-POLL.confirm primitive with a Status of SUCCESS. In this case, the actual data are indicated to the next higher layer using the MCPS-DATA.indication primitive, as described in 8.3.6.

If a frame is not received at the expected time even though the acknowledgment to the Data Request command has its Frame Pending field set to one, the MLME will issue the MLME-POLL.confirm primitive with a Status of NO_DATA.

10.23 Promiscuous mode

10.23.1 Overview of promiscuous mode

A device may activate promiscuous mode by setting *macPromiscuousMode*. If the MLME is requested to set *macPromiscuousMode* to TRUE, the MLME shall then request that the PHY enable its receiver.

When in promiscuous mode, the MAC sublayer shall process received frames according to 6.6.2 and pass all frames correctly received to the next higher layer using the MCPS-DATA.indication primitive. The only valid parameters of the MCPS-DATA.indication primitive are Msdu, MpduLinkQuality, Timestamp, and Rssi. The Msdu parameter shall contain the MHR concatenated with the MAC payload, as illustrated in Figure 7-1.

If the MLME is requested to set *macPromiscuousMode* to FALSE, the MLME shall request that the PHY set its receiver to the state specified by *macRxOnWhenIdle*.

10.23.2 MAC constants and PIB attributes for promiscuous mode

Promiscuous mode attributes are described in Table 10-114.

Table 10-114—Promiscuous mode related PIB attributes

Attribute	Type	Range	Description	Default
<i>macPromiscuousMode</i> *	Boolean	TRUE, FALSE	Indication of whether the MAC sublayer is in a promiscuous (receive all) mode. A value of TRUE indicates that the MAC sublayer accepts all frames received from the PHY.	FALSE

10.24 Device Announcement (DA)

10.24.1 Overview

To facilitate data transfer effectively between two or more peer devices, a device announces its address and its neighbors' addresses to its neighbor devices by broadcasting beacons with a Device Announcement (DA) IE, as defined in 10.24.2.1. A DA IE shall only be sent in an Enhanced Beacon frame.

A device shall broadcast an Enhanced Beacon frame with a DA IE upon receiving an MLME-DA.request primitive, as defined in 10.24.3.1, from the next higher layer. It may also broadcast beacons with a DA IE at other times. After transmitting an Enhanced Beacon frame with the DA IE requested by an MLME-DA.request, the device shall send an MLME-DA.confirm, as described in 10.24.3.3, to the next higher layer.

Upon receiving an Enhanced Beacon frame with a DA IE, a device shall indicate the address of the transmitting device and the addresses list in the DA IE to its next higher layer using the MLME-DA.indication primitive 10.24.3.2. A device may check whether or not its address is known at the transmitting device by tracking the received Enhanced Beacon frames with a DA IE. If not, the device may broadcast an Enhanced Beacon with a DA IE to announce its address at the appropriate time.

The message sequence chart for an Enhanced Beacon with a DA IE to announce the address of a device and its neighbors' addresses is illustrated in Figure 10-162.

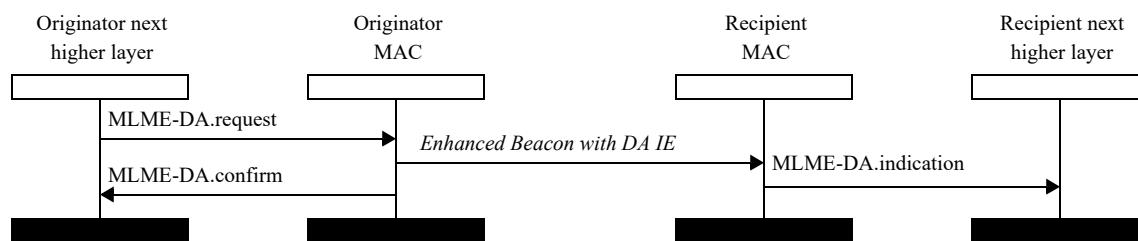


Figure 10-162—Sending DA IE message sequence chart

10.24.2 Header IEs for DA

10.24.2.1 DA IE

The DA IE Content field shall be formatted as illustrated in Figure 10-163.

Bits: 0	1	2–5	6–15	16–20	21–23	variable
Address Mode	Addresses Pending	Reserved	Number of Addresses	Sequence Number	Page Number	Address List

Figure 10-163—DA IE Content field format

When the Address Mode field is set to zero, each address included in Address List is a short address. When Address Mode field is set to one, each address included in Address List is an extended address.

The Number of Addresses field is the number of neighbor addresses included in the Address List field of this DA IE.

The Addresses Pending field shall be set to one when the set of neighbor addresses is to be announced in multiple Beacon frames. An Addresses Pending field set to one indicates that this IE contains a subset of the set of neighbor addresses known by the device and that more neighbor addresses are to be sent in following Beacon frames with a DA IE.

The Sequence Number field shall be set to a value identifying the set of addresses to be announced. An increment in the Sequence Number indicates that a new set of neighbor addresses is being announced. The Sequence Number shall be incremented when any address in the set of neighbor addresses has been changed.

The Page Number field shall be set to one for the first subset of address and incremented by one for each subsequent subset of addresses.

The Addresses Pending field shall be set to zero when the set of addresses to be announced is contained in a single DA IE. When the Addresses Pending field is set to zero, the Sequence Number and Page Number fields shall be set to zero.

The Address List field contains the addresses of the device's neighbors.

10.24.3 MAC management service primitives for DA

10.24.3.1 MLME-DA.request primitive

The MLME-DA.request primitive requests that the device announce its address to neighbor devices.

The semantics of this primitive are as follows:

```
MLME-DA.request      (
    CoordAddrMode,
    CoordPanId,
    CoordAddress,
    DaAddrMode,
    DaAddrList
)
```

The primitive parameters are defined in Table 10-115.

Table 10-115—MLME-DA.request parameters

Name	Type	Valid range	Description
CoordAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the coordinator to which this device is associated.
CoordPanId	Integer	0x0000–0xffff	The identifier of the PAN to which this device is associated.
CoordAddress	—	As specified by the CoordAddrMode parameter	The address of the coordinator to which this device is associated.
DaAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the neighbors' addresses to be transmitted.
DaAddrList	Addresses list	As specified by the DaAddrMode parameter	The neighbors' addresses list to be sent.

10.24.3.2 MLME-DA.indication primitive

The MLME-DA.indication primitive indicates reception addresses with a DA IE.

The semantics of this primitive are as follows:

```
MLME-DA.indication      (
    CoordAddrMode,
    CoordPanId,
    CoordAddress,
    AddrMode,
    Address,
    DaAddrMode,
    DaAddrList
)
```

The primitive parameters are defined in Table 10-116.

When the MAC has received all the DA IEs sent by the transmitting device, the MAC passes the addresses to the next higher layer using the MLME-DA.indication primitive.

Table 10-116—MLME-DA.indication parameters

Name	Type	Valid range	Description
CoordAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the coordinator with which the transmitting device is associated.
CoordPanId	Integer	0x0000–0xffff	The identifier of the PAN with which the transmitting device is associated.
CoordAddress	—	As specified by the CoordAddrMode parameter	The address of the coordinator with which the transmitting device is associated.
AddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the transmitting device.
Address	—	As specified by the AddrMode parameter	The address of the transmitting device.
DaAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the addresses included in the Address List field of a DA IE.
DaAddrList	Set of addresses	As specified by the DaAddrMode parameter	The addresses included in a DA IE.

10.24.3.3 MLME-DA.confirm primitive

The MLME-DA.confirm primitive reports results of broadcasting the beacon frame with DA IE.

The semantics of this primitive are as follows:

```
MLME-DA.confirm      (
    Status
)
```

The primitive parameter is defined in Table 10-117.

Table 10-117—MLME-DA.confirm parameter

Name	Type	Valid range	Description
Status	Enumeration	SUCCESS, FAILURE	The results of broadcasting a beacon frame with DA IE.

10.25 Guaranteed timeslot (GTS)

10.25.1 GTS general requirements

A GTS allows a device to operate on the channel within a portion of the superframe that is dedicated (on the PAN) exclusively to that device. The use of GTSSs is optional.

A GTS shall be allocated only by the PAN coordinator, and it shall be used only for communications between the PAN coordinator and a device associated with the PAN through the PAN coordinator. A single GTS may extend over one or more superframe slots. The PAN coordinator may allocate up to seven GTSSs at the same time, provided there is sufficient capacity in the superframe.

A GTS shall be allocated before use, with the PAN coordinator deciding whether to allocate a GTS based on the requirements of the GTS Request command and the current available capacity in the superframe. GTSs shall be allocated on a first-come-first-served basis, and all GTSs shall be placed contiguously at the end of the superframe and after the CAP. Each GTS shall be deallocated when the GTS is no longer required, and a GTS can be deallocated at any time at the discretion of the PAN coordinator or by the device that originally requested the GTS. A device that has been allocated a GTS may also operate in the CAP.

A Data frame transmitted in an allocated GTS shall use only short addressing.

The management of GTSs shall be undertaken by the PAN coordinator only. To facilitate GTS management, the PAN coordinator shall be able to store all the information necessary to manage seven GTSs. For each GTS, the PAN coordinator shall be able to store its starting slot, length, direction, and associated device address.

The GTS direction, which is relative to the data flow from the device that owns the GTS, is specified as either transmit or receive. The device address and direction shall, therefore, uniquely identify each GTS. Each device may request one transmit GTS and/or one receive GTS. For each allocated GTS, the device shall be able to store its starting slot, length, and direction. If a device has been allocated a receive GTS, it shall enable its receiver for the entirety of the GTS. In the same way, the PAN coordinator shall enable its receiver for the entirety of the GTS if a device has been allocated a transmit GTS. If a Data frame is received during a receive GTS and an acknowledgment is requested, the device shall transmit the Ack frame as usual. Similarly, a device shall be able to receive an Ack frame during a transmit GTS.

A device shall attempt to allocate and use a GTS only if it is currently tracking the beacons. The MLME is instructed to track beacons by issuing the MLME-SYNC.request primitive with the TrackBeacon parameter set to TRUE. If a device loses synchronization with the PAN coordinator, all its GTS allocations shall be lost.

10.25.2 CAP maintenance

The PAN coordinator shall preserve the minimum CAP length of $aMinCapLength$ and take preventative action if the minimum CAP is not satisfied. However, an exception shall be allowed for the accommodation of the temporary increase in the Beacon frame length needed to perform GTS maintenance. If preventative action becomes necessary, the action chosen is left up to the implementation but may include one or more of the following:

- Limiting the number of pending addresses included in the beacon
- Not including a payload field in the Beacon frame
- Deallocation of one or more of the GTSs

10.25.3 GTS allocation

A device is instructed to request the allocation of a new GTS through the MLME-GTS.request primitive, as described in 10.25.10.2, with GTS characteristics set according to the requirements of the intended application.

To request the allocation of a new GTS, the MLME shall send the GTS Request command, as described in 10.25.9.1, to the PAN coordinator. The Characteristics Type field of the GTS Characteristics field of the request shall be set to one (GTS allocation), and the length and direction fields shall be set according to the desired characteristics of the required GTS.

On receipt of a GTS Request command indicating a GTS allocation request, the PAN coordinator shall first check if there is available capacity in the current superframe, based on the remaining length of the CAP and

the desired length of the requested GTS. The superframe shall have available capacity if the maximum number of GTSs has not been reached and allocating a GTS of the desired length would not reduce the length of the CAP to less than $aMinCapLength$. GTSs shall be allocated on a first-come-first-served basis by the PAN coordinator provided there is sufficient bandwidth available. The PAN coordinator shall make this decision within $aGtsDescPersistenceTime$.

On receipt of the acknowledgment to the GTS Request command, the device shall continue to track beacons and wait for at most $aGtsDescPersistenceTime$. If no GTS descriptor for the device appears in the beacon within this time, the MLME of the device shall notify the next higher layer of the failure. This notification is achieved when the MLME issues the MLME-GTS.confirm primitive, as described in 10.25.10.3, with a Status of NO_DATA.

When the PAN coordinator determines whether capacity is available for the requested GTS, it shall generate a GTS descriptor with the requested specifications and the short address of the requesting device. If the GTS was allocated successfully, the PAN coordinator shall set the start slot in the GTS descriptor to the superframe slot at which the GTS begins and the length in the GTS descriptor to the length of the GTS. In addition, the PAN coordinator shall notify the next higher layer of the new GTS. This notification is achieved when the MLME of the PAN coordinator issues the MLME-GTS.indication primitive, as described in 10.25.10.4, with the characteristics of the allocated GTS. If there was not sufficient capacity to allocate the requested GTS, the start slot shall be set to zero and the length to the largest GTS length that can currently be supported. The PAN coordinator shall then include this GTS descriptor in its beacon and update the GTS Specification field of the Beacon frame accordingly. The PAN coordinator shall also update the Final CAP Slot field of the Superframe Specification field of the Beacon frame, indicating the final superframe slot utilized by the decreased CAP. The GTS descriptor shall remain in the Beacon frame for $aGtsDescPersistenceTime$ superframes, after which it shall be removed automatically. The PAN coordinator shall be allowed to reduce its CAP below $aMinCapLength$ to accommodate the temporary increase in the Beacon frame length due to the inclusion of the GTS descriptor.

On receipt of a Beacon frame containing a GTS descriptor corresponding to $macShortAddress$, the device shall process the descriptor. The MLME of the device shall then notify the next higher layer of whether the GTS allocation request was successful. This notification is achieved when the MLME issues the MLME-GTS.confirm primitive with a Status of SUCCESS (if the start slot in the GTS descriptor was greater than zero) or DENIED (if the start slot was equal to zero or if the length did not match the requested length).

Figure 10-164 illustrates the message flow for the case in which the device requests the GTS allocation.

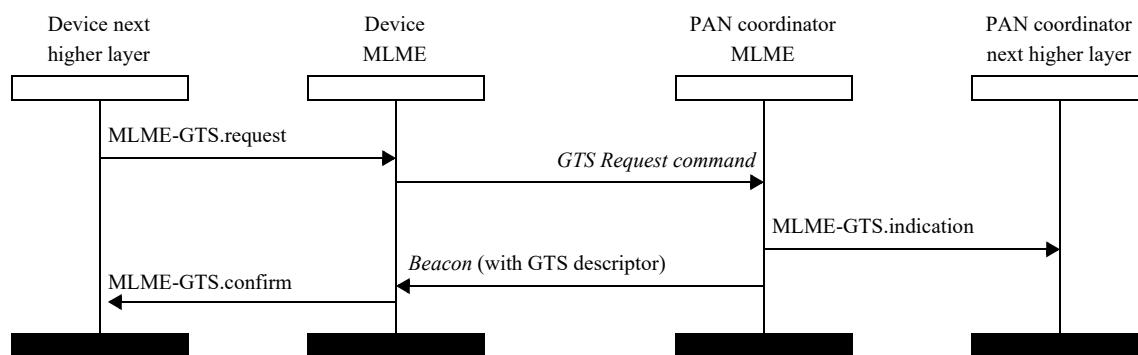


Figure 10-164—Message sequence chart for GTS allocation initiated by a device

10.25.4 GTS usage

When the MAC sublayer of a device that is not the PAN coordinator receives an MCPS-DATA.request primitive, as described in 8.3.4, with the TxOptions parameter indicating a GTS transmission, it shall determine whether it has a valid transmit GTS. If a valid GTS is found, the MAC sublayer shall transmit the data during the GTS, i.e., between its starting slot and its starting slot plus its length. At this time, the MAC sublayer shall transmit the MPDU immediately without using CSMA-CA, provided the requested transaction can be completed before the end of the GTS. If the requested transaction cannot be completed before the end of the current GTS, the MAC sublayer shall defer the transmission until the specified GTS in the next superframe.

If the device has any receive GTSs, the MAC sublayer of the device shall enable the receiver at a time prior to the start of the GTS and for the duration of the GTS, as indicated by its starting slot and its length.

When the MAC sublayer of the PAN coordinator receives an MCPS-DATA.request primitive with the TxOptions parameter indicating a GTS transmission, it shall determine whether it has a valid receive GTS corresponding to the device with the requested destination address. If a valid GTS is found, the PAN coordinator shall defer the transmission until the start of the receive GTS. In this case, the address of the device with the message requiring a GTS transmission shall not be added to the set of pending addresses in the Beacon frame, as described in 10.22.2. At the start of the receive GTS, the MAC sublayer shall transmit the data without using CSMA-CA, provided the requested transaction can be completed before the end of the GTS. If the requested transaction cannot be completed before the end of the current GTS, the MAC sublayer shall defer the transmission until the specified GTS in the next superframe.

For all allocated transmit GTSs (relative to the device), the MAC sublayer of the PAN coordinator shall enable its receiver at a time prior to the start and for the duration of each GTS.

Before commencing transmission in a GTS, each device shall ensure that the data transmission, the acknowledgment, if requested, and the IFS, suitable to the size of the Data frame, can be completed before the end of the GTS.

If a device misses the beacon at the beginning of a superframe, it shall not use its GTSs until it receives a subsequent beacon correctly. If a loss of synchronization occurs due to the loss of the beacon, the device shall consider all of its GTSs deallocated.

10.25.5 GTS deallocation

A device is instructed to request the deallocation of an existing GTS through the MLME-GTS.request primitive, as described in 10.25.10.2, using the characteristics of the GTS that it wishes to deallocate. From this point onward, the GTS to be deallocated shall not be used by the device, and its stored characteristics shall be reset.

To request the deallocation of an existing GTS, the MLME shall send the GTS Request command, as described in 10.25.9.1, to the PAN coordinator. The Characteristics Type field of the GTS Characteristics field of the request shall be set to zero (i.e., GTS deallocation), and the length and direction fields shall be set according to the characteristics of the GTS to deallocate. On receipt of the acknowledgment to the GTS Request command, the MLME shall notify the next higher layer of the deallocation. This notification is achieved when the MLME issues the MLME-GTS.confirm primitive, as described in 10.25.10.3, with a Status of SUCCESS and a GTSCharacteristics parameter with its Characteristics Type field set to zero. If the GTS Request command is not received correctly by the PAN coordinator, it shall determine that the device has stopped using its GTS by the procedure described in 10.25.7.

On receipt of a GTS Request command with the Characteristics Type field of the GTS Characteristics field set to zero (GTS deallocation), the PAN coordinator shall attempt to deallocate the GTS. If the GTS

characteristics contained in the GTS Request command do not match the characteristics of a known GTS, the PAN coordinator shall ignore the request. If the GTS characteristics contained in the GTS Request command match the characteristics of a known GTS, the MLME of the PAN coordinator shall deallocate the specified GTS and notify the next higher layer of the change. This notification is achieved when the MLME issues the MLME-GTS.indication primitive, as described in 10.25.10.4, with a GTSCharacteristics parameter containing the characteristics of the deallocated GTS and a Characteristics Type field set to zero. The PAN coordinator shall also update the Final CAP Slot field of the Superframe Specification field of the Beacon frame, indicating the final superframe slot utilized by the increased CAP. It shall not add a descriptor to the Beacon frame to describe the deallocation.

GTS deallocation may be initiated by the PAN coordinator due to a deallocation request from the next higher layer, the expiration of the GTS, as described in 10.25.7, or maintenance required to maintain the minimum CAP length, $aMinCapLength$, as described in 10.25.2.

The next higher layer of the PAN coordinator initiates a GTS deallocation using an MLME-GTS.request primitive with the GTS Characteristics field of the request set to indicate a GTS deallocation and the length and direction fields set according to the characteristics of the GTS to deallocate. The MLME shall then respond with an MLME-GTS.confirm primitive with a Status of SUCCESS and the GTSCharacteristics parameter with a Characteristics Type field set to zero.

When a GTS deallocation is initiated by the PAN coordinator either due to the GTS expiring or due to CAP maintenance, the MLME shall notify the next higher layer of the change using the MLME-GTS.indication primitive with a GTSCharacteristics parameter containing the characteristics of the deallocated GTS and a Characteristics Type field set to zero.

In the case of any deallocation initiated by PAN coordinator, the PAN coordinator shall deallocate the GTS and add a GTS descriptor into its Beacon frame corresponding to the deallocated GTS, but with its starting slot set to zero. The descriptor shall remain in the Beacon frame for $aGtsDescPersistenceTime$ superframes. The PAN coordinator shall be allowed to reduce its CAP below $aMinCapLength$ to accommodate the temporary increase in the Beacon frame length due to the inclusion of the GTS descriptor.

On receipt of a Beacon frame containing a GTS descriptor corresponding to $macShortAddress$ and a start slot equal to zero, the device shall immediately stop using the GTS. The MLME of the device shall then notify the next higher layer of the deallocation using the MLME-GTS.indication primitive with a GTSCharacteristics parameter containing the characteristics of the deallocated GTS and a Characteristics Type field set to zero.

Figure 10-165 depicts the message flow for the cases in which a GTS deallocation is initiated by a device.

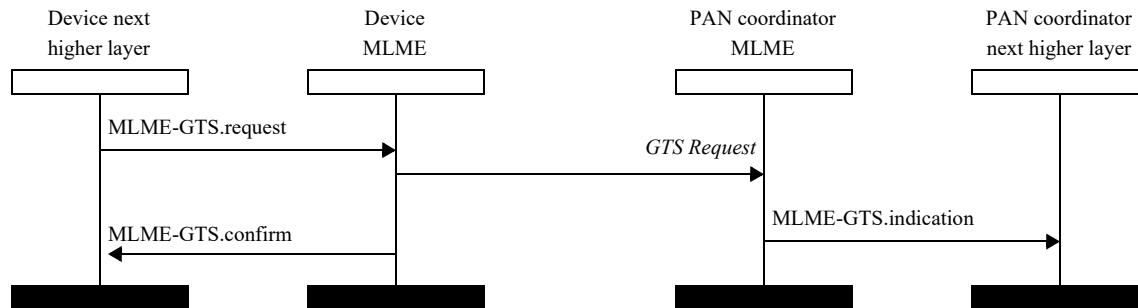


Figure 10-165—Message sequence chart for GTS deallocation initiated by a device

Figure 10-166 depicts the message flow for the cases in which a GTS deallocation is initiated by the PAN coordinator.

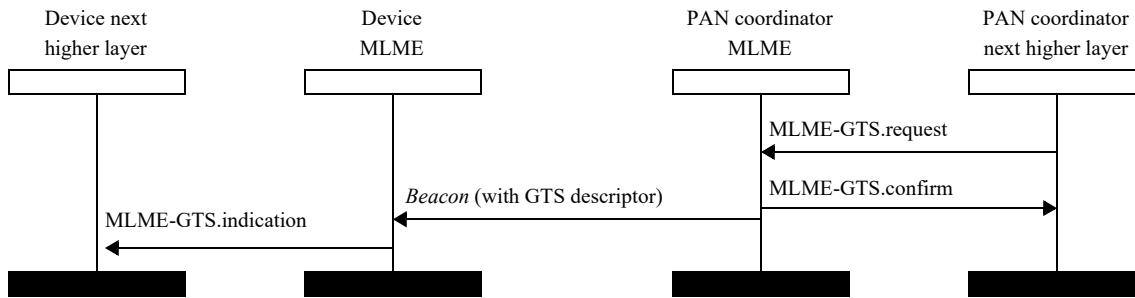


Figure 10-166—Message sequence chart for GTS deallocation initiated by the PAN coordinator

10.25.6 GTS reallocation

The deallocation of a GTS may result in the superframe becoming fragmented. For example, Figure 10-167 shows three stages of a superframe with allocated GTSs. In stage 1, three GTSs are allocated starting at slots 8, 10, and 14, respectively. If GTS 2 is now deallocated (stage 2), there will be a gap in the superframe during which nothing can happen. To solve this, GTS 3 will have to be shifted to fill the gap, thus increasing the size of the CAP (stage 3).

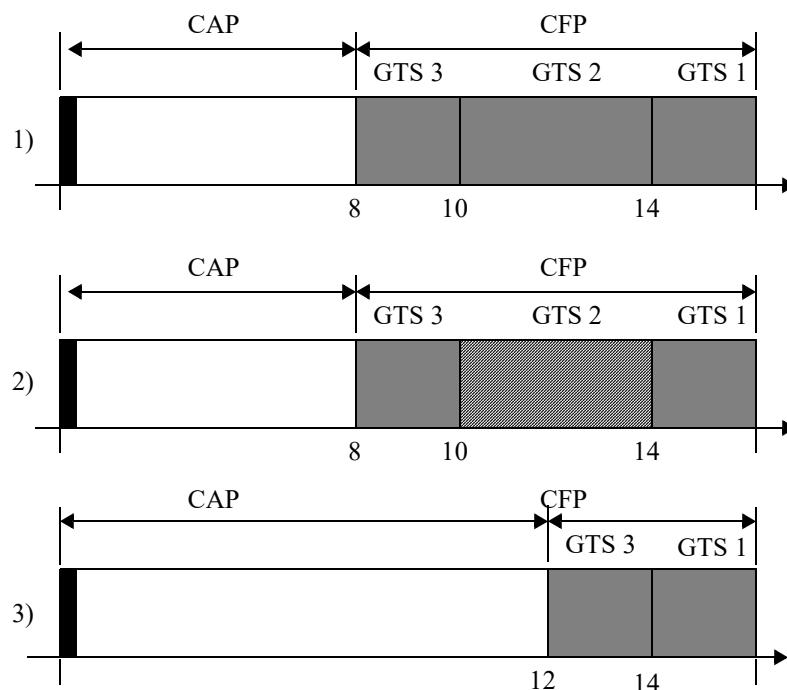


Figure 10-167—CFP defragmentation on GTS deallocations

The PAN coordinator shall remove any gaps occurring in the CFP, due to the deallocation of a GTS.

When a GTS is deallocated by the PAN coordinator, it shall add a GTS descriptor into its Beacon frame indicating that the GTS has been deallocated. If the deallocation is initiated by a device, the PAN coordinator shall not add a GTS descriptor into its Beacon frame to indicate the deallocation. For each

device with an allocated GTS having a starting slot lower than the GTS being deallocated, the PAN coordinator shall update the GTS with the new starting slot and add a GTS descriptor to its beacon corresponding to this adjusted GTS. The new starting slot is computed so that no space is left between this GTS and either the end of the CFP, if the GTS appears at the end of the CFP, or the start of the next GTS in the CFP.

In situations where multiple reallocations occur at the same time, the PAN coordinator may choose to perform the reallocation in stages. The PAN coordinator shall keep each GTS descriptor in its beacon for $aGtsDescPersistenceTime$ superframes.

On receipt of a Beacon frame containing a GTS descriptor corresponding to $macShortAddress$ and a direction and length corresponding to one of its GTSSs, the device shall adjust the starting slot of the GTS corresponding to the GTS descriptor and start using it immediately.

In cases where it is necessary for the PAN coordinator to include a GTS descriptor in its beacon, it shall be allowed to reduce its CAP below $aMinCapLength$ to accommodate the temporary increase in the Beacon frame length. After $aGtsDescPersistenceTime$ superframes, the PAN coordinator shall remove the GTS descriptor from the beacon.

10.25.7 GTS expiration

The MLME of the PAN coordinator shall attempt to detect when a device has stopped using a GTS using the following rules:

- For a transmit GTS, the MLME of the PAN coordinator shall assume that a device is no longer using its GTS if a Data frame is not received from the device in the GTS at least every $2 \times n$ superframes, where n is defined below.
- For receive GTSSs, the MLME of the PAN coordinator shall assume that a device is no longer using its GTS if an Ack frame is not received from the device at least every $2 \times n$ superframes, where n is defined below. If the Data frames sent in the GTS do not require Ack frames, the MLME of the PAN coordinator will not be able to detect whether a device is using its receive GTS. However, the PAN coordinator is capable of deallocating the GTS at any time.

The value of n is defined as follows:

$$n = 2^{(8-macBeaconOrder)} \quad 0 \leq macBeaconOrder \leq 8$$

$$n = 1 \quad 9 \leq macBeaconOrder \leq 14$$

10.25.8 Header IEs for GTS

10.25.8.1 Simplified GTS Specification IE

The Simplified GTS Specification IE Content field shall be formatted as illustrated in Figure 10-168.

Octets: 1	variable
GTS Directions	GTS Device Address List

Figure 10-168—Simplified GTS Specification IE Content field format

The GTS Directions field is defined in 7.3.1.5.

The GTS Device Address List field is defined in 7.3.1.5.

10.25.9 MAC commands for GTS

10.25.9.1 GTS request command

Only devices that have been assigned a short address shall send a GTS Request command. This command is optional.

The Destination Addressing Mode field shall be set to indicate that destination addressing information is not present, and the Source Addressing Mode field shall be set to indicate short addressing.

The Frame Pending field shall be set to zero and ignored upon reception, and the AR field shall be set to one.

The Source PAN ID field shall contain the value of *macPanId*, and the Source Address field shall contain the value of *macShortAddress*.

The GTS Request command Content field shall be formatted as illustrated in Figure 10-169.

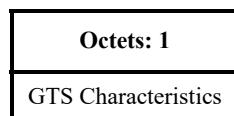


Figure 10-169—GTS Request command Content field format

The GTS Characteristics field shall be formatted as illustrated in Figure 10-170.

Bits: 0–3	4	5	6–7
GTS Length	GTS Direction	Characteristics Type	Reserved

Figure 10-170—GTS Characteristics field format

The GTS Length field shall contain the number of superframe slots being requested for the GTS.

The GTS Direction field shall be set to one if the GTS is to be a receive-only GTS. Conversely, this field shall be set to zero if the GTS is to be a transmit-only GTS. GTS direction is defined relative to the direction of Data frame transmissions by the device.

The Characteristics Type field shall be set to one if the characteristics refer to a GTS allocation or zero if the characteristics refer to a GTS deallocation.

10.25.10 MAC management service primitives for GTS

10.25.10.1 General

These primitives are used to request and maintain GTSs.

10.25.10.2 MLME-GTS.request

The MLME-GTS.request primitive allows a device to send a request to the PAN coordinator to allocate a new GTS or to deallocate an existing GTS. This primitive is also used by the PAN coordinator to initiate a GTS deallocation.

The semantics of this primitive are as follows:

```
MLME-GTS.request      (
    GtsCharacteristics,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-118.

Table 10-118—MLME-GTS.request parameters

Name	Type	Valid range	Description
GtsCharacteristics	GTS characteristics	As defined in 10.25.9.1	The characteristics of the GTS request, including whether the request is for the allocation of a new GTS or the deallocation of an existing GTS.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

On receipt of the MLME-GTS.request primitive by a device, the MLME of a device performs either the GTS request procedure, as described in 10.25.3, or the GTS deallocation procedure, as described in 10.25.5, depending on the value of the GTSCharacteristics field.

10.25.10.3 MLME-GTS.confirm

The MLME-GTS.confirm primitive reports the results of a request to allocate a new GTS or to deallocate an existing GTS.

The semantics of this primitive are as follows:

```
MLME-GTS.confirm      (
    GtsCharacteristics,
    Status
)
```

The primitive parameters are defined in Table 10-119.

Table 10-119—MLME-GTS.confirm parameters

Name	Type	Valid range	Description
GtsCharacteristics	GTS characteristics	As defined in 10.25.9.1	The characteristics of the GTS.
Status	Enumeration	SUCCESS, DENIED, NO_SHORT_ADDRESS, NO_DATA, also see 8.2.2	The status of the GTS request.

If the request to allocate or deallocate a GTS was successful, this primitive will return a Status of SUCCESS, and the Characteristics Type field of the GtsCharacteristics parameter will have the value of one or zero, respectively. Otherwise, the Status parameter will indicate the appropriate error code, as defined in 10.25.3 or 10.25.5.

If *macShortAddress* is equal to 0xffffe or 0xffff, the device is not permitted to request a GTS, and the Status parameter will be set to NO_SHORT_ADDRESS.

10.25.10.4 MLME-GTS.indication

The MLME-GTS.indication primitive indicates that a GTS has been allocated or that a previously allocated GTS has been deallocated.

The semantics of this primitive are as follows:

```
MLME-GTS.indication (DeviceAddress, GtsCharacteristics, SecurityParams)
```

The primitive parameters are defined in Table 10-120.

Table 10-120—MLME-GTS.indication parameters

Name	Type	Valid range	Description
DeviceAddress	Short address	0x0000–0xffffd	The short address of the device that has been allocated or deallocated a GTS.
GtsCharacteristics	GTS characteristics	As defined in 10.25.9.1	The characteristics of the GTS.
SecurityParams	Structure	As defined in Table 8-2	If the primitive was generated when a GTS deallocation was initiated by the PAN coordinator itself, this parameter is ignored. Otherwise as defined in Table 8-2.

The value of the Characteristics Type field, as defined in 10.25.9.1, in the GtsCharacteristics parameter indicates if the GTS has been allocated or if a GTS has been deallocated.

10.25.11 MAC constants and PIB attributes for GTS

The constants related to the GTS are presented in Table 10-121.

Table 10-121—MAC constant for GTS

Constant	Description	Value
<i>aGtsDescPersistenceTime</i>	The number of superframes in which a GTS descriptor exists in the beacon frame of the PAN coordinator.	4

10.26 PHY parameters change notification procedure

10.26.1 Signaling using Beacon frames

This method is initiated by the reception of the MLME-PHY-OP-SWITCH.request primitive with the SignalMethod parameter value set to USE_BEACON. The method requires that the Enhanced Beacon frames are supported and that the device is the PAN coordinator using Enhanced Beacon frames. If these conditions are not met, the device shall respond with the MLME-PHY-OP-SWITCH.confirm primitive having the appropriate Status parameter value indicating the reason for the request failure.

A PHY Parameter Change IE, as defined in 10.26.3.1, shall be generated and inserted in the next outgoing Enhanced Beacon frame. The Effective Time of Change field of the IE shall be set to the value of the TargetTime parameter of the MLME-PHY-OP-SWITCH.request primitive. The Notification Time field shall be updated with the local time of the device each time it is transmitted. The appropriate operating mode description IE as described in Table 10-122 shall be generated according to the values in the PhyParameterList and inserted in the same Enhanced Beacon frame following the PHY Parameter Change IE.

If the value of the RepeatCount parameter of the MLME-PHY-OP-SWITCH.request primitive is nonzero, then the generated IEs shall be included in each Enhanced Beacon frame subsequently generated until the repeat count is exhausted or until the value in the TargetTime parameter has elapsed. If the RepeatCount parameter is zero, the generated IEs shall be included in only the next Enhanced Beacon frame.

Table 10-122—Operating mode description IEs

PHY	Operating mode description IE	Reference
RCC PHY	RCC PHY Operating Mode IE	10.13.4.1
SUN PHY	SUN Device Capabilities IE	10.14.3.1
LECIM PHY	LECIM DSSS Operating Mode IE	10.15.3.1
	LECIM FSK Operating Mode IE	10.15.3.2
	LECIM FSK Split Operating Mode IE	10.15.3.3
TVWS PHY	TVWS PHY Operating Mode Description IE	10.7.3.1
RS-GFSK PHY	RS-GFSK Device Capabilities IE	10.26.3.3
O-QPSK PHY	O-QPSK PHY Mode IE	10.26.3.2

10.26.2 Signaling using multipurpose frames

This method is initiated by the reception of the MLME-PHY-OP-SWITCH.request primitive with the SignalMethod parameter value set to USE_MP. The method requires that the multipurpose frame, as defined in 7.3.5, is supported. If this condition is not met, the device shall respond with the MLME-PHY-OP-SWITCH.confirm primitive having the appropriate Status parameter value.

The device shall generate a PHY Op Mode Switch frame, which is a Multipurpose frame containing a PHY Parameter Change IE and an operating mode description IE. The addressing fields shall be set according to the DeviceAddrMode and DeviceAddr parameter values in the MLME-PHY-OP-SWITCH.request primitive. If the DeviceAddress parameter contains the broadcast address, then only the PAN ID addressing field shall be included, and it shall be set to the broadcast PAN ID. The PHY Parameter Change IE and an

operating mode description IE shall be generated using the TargetTime, RepeatCount, and PhyParameterList parameters, as described in 10.26.1.

For a directed PHY Op Mode Switch frame, the frame shall be generated with the AR field in the MHR set to request an acknowledgment and transmitted according to 6.6.

If the RepeatCount parameter value is greater than zero, the MLME shall repeat transmission of the frame after a delay equal to the value of the RepeatInterval parameter until the RepeatCount parameter value is exhausted. The Notification Time field shall be updated with the local time of the device each time it is transmitted.

When the TxIndirect parameter is set to TRUE, the PHY Op Mode Switch frame shall be sent using indirect transmission, as described in 10.22.2.

10.26.3 Nested IEs for PHY parameters change

10.26.3.1 PHY Parameter Change IE

The PHY Parameter Change IE Content field shall be formatted as illustrated in Figure 10-171.

Octets: 4	4
Effective Time of Change	Notification Time

Figure 10-171—PHY Parameter Change IE

The Effective Time of Change field shall contain a time in the future, in microseconds, when the change is scheduled to occur.

The Notification Time field shall contain the local time value in the generating device at the time the frame containing the PHY Parameter Change IE is generated.

The PHY Parameter Change IE shall always be followed in the frame by a valid operating mode description IE.

10.26.3.2 O-QPSK PHY Mode IE

The O-QPSK PHY Mode IE Content field shall be formatted as illustrated in Figure 10-172.

Octets: 1	1
Band Selector	Channel Index

Figure 10-172—O-QPSK PHY Mode IE Content field format

The Band Selector field identifies the band for the operating mode and shall take one of the non-reserved values in Table 10-123.

The Channel Index field shall contain a valid channel number as defined in 11.1.3.2, 11.1.3.3, or 11.1.3.10, as appropriate to the band selector value.

Table 10-123—Band Selector frequency bands

Band Selector value	Corresponding band
0	Reserved
1	780 MHz band
2	868 MHz band
3	915 MHz band
4	2380 MHz band
5	2450 MHz band
6–7	Reserved

10.26.3.3 RS-GFSK Device Capabilities IE

The RS-GFSK Device Capabilities IE is optional and only valid for the RS-GFSK PHY. The RS-GFSK Device Capabilities IE Content field shall be formatted as illustrated in Figure 10-173.

Octets: 1	2	2
RS-GFSK Features	Frequency Bands Supported	PHY MCS Levels Supported

Figure 10-173—RS-GFSK Device Capabilities IE Content field format

The RS-GFSK Features field shall be formatted as illustrated in Figure 10-174.

Bits: 0	1	2	3	4–7
Rate Switch	Short PHR	FEC	Link Margin	Reserved

Figure 10-174—RS-GFSK Features field format

The Rate Switch field shall be set to one if rate switch mode, as described in 32.3, is supported and shall be set to zero otherwise.

The Short PHR field shall be set to one if the short PHR, as defined in 32.1.5, is supported and shall be set to zero otherwise. When the short PHR is supported, the device shall be responsive to both states of the received Short PHR bit in the PHY header as described in 32.1.4 and 32.1.5. It also means that the device shall be capable of transmitting a Short PHR field as described in 32.1.5 and a Long PHR as described in 32.1.4.

The FEC field shall be set to one if FEC, as described in 32.2.8, is supported and shall be set to zero otherwise. When the FEC field is set to one, the device shall be responsive to the received SFD as described in 32.1.3 and 32.2.8 in both FEC enabled and FEC disabled cases. It also means that the device is capable of transmitting with FEC enabled as described in 32.1.3 and 32.2.8; however, it may transmit without FEC enabled.

The Link Margin field in Figure 10-174 shall be set to one if acting on the Link Margin IE, as described in 10.28.6.1, is supported and shall be set to zero otherwise. When the Link Margin field is set to one, the

device shall be responsive to the received Link Margin IE as described in 10.28.6.1, when its control range allows.

The Frequency Bands Supported field is a bitmap in which bit n shall be set to one if the frequency band in Table 11-7 associated with the frequency band identifier n is supported and shall be set to zero otherwise. The unused bit in the Frequency Bands Supported field is reserved. The supported frequency bands shall be supported in both transmit and receive.

The PHY MCS Levels Supported field is a bitmap in which bit n shall be set to one if the MCS in Table 32-2 associated with the RS-GFSK MCS mode n is supported and shall be set to zero otherwise. The unused bits in the PHY MCS Levels Supported field are reserved. When rate switch is supported, for each of the supported 2-GFSK MCS, there shall be an operating mode from Table 32-3 that will provide double data rate, as described in 32.3. A device shall be capable of receiving the MCS as indicated in its transmitted RS-GFSK Device Capabilities IE. The device is permitted to transmit in any other MCS.

This IE is used by the higher layer and MAC and may be transmitted as part of an Enhanced Beacon frame, a Data frame, a MAC Command frame, and a Multipurpose frame.

10.26.3.4 Multi-PHY IE

The Multi-PHY IE is optional. The Multi-PHY IE Content field shall be formatted as illustrated in Figure 10-175.

Octets: 1	2	2
RS-GFSK Features	Frequency Bands Supported	PHY MCS Levels Supported

Figure 10-175—Multi-PHY IE Content field format

The value of the field shall be set to one when the device sending the IE supports the corresponding PHY and shall be set to zero otherwise.

10.26.4 MAC management service primitives for PHY parameters change

10.26.4.1 General

These primitives support the coordination of a change in PHY operating parameters among peer devices.

10.26.4.2 MLME-PHY-OP-SWITCH.request

The MLME-PHY-OP-SWITCH.request primitive is used by a device to instruct a second device to switch PHY operating parameters, including channel, band, PHY type, or other parameters specific to a PHY.

The semantics of this primitive are as follows:

```
MLME-PHY-OP-SWITCH.request ( 
    DeviceAddrMode,
    DeviceAddr,
    PhyParameterList,
    TxIndirect,
    TargetTime,
    SignalMethod,
    RepeatCount,
    RepeatInterval,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-124.

Table 10-124—MLME-PHY-OP-SWITCH.request parameters

Name	Type	Valid range	Description
DeviceAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the device being instructed to change its operating parameters.
DeviceAddr	Short address or extended address	As specified by the DeviceAddrMode parameter	The address of the device being instructed to change its operating parameters.
PhyParameterList	List of PHY PIB attributes and values	As defined in 12.3	A list of the PHY PIB attribute names and values representing the PHY operating parameters to be changed.
TxIndirect	Boolean	TRUE, FALSE	When the TxIndirect parameter is set to TRUE, the multipurpose frame shall be sent using indirect transmission. When the parameter is set to FALSE, the multipurpose frame shall be sent using direct transmission.
TargetTime	Integer	0–(2 ³² – 1)	The time, in microseconds, from the current time that the PHY operating parameter switch is to be carried out.
SignalMethod	Enumeration	USE_MP, USE_BEACON	The method to be used to signal intended switch.
RepeatCount	Integer	0–127	Number of times that the notification containing the PHY Parameter Change IE is repeated.
RepeatInterval	Integer	0–0xffff	The time, in microseconds, to delay between repeated transmissions.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

On receipt of the MLME-PHY-OP-SWITCH.request primitive, the MLME initiates the PHY parameter change notification procedure, as defined in 10.26.

If the device is the PAN coordinator of a PAN using superframe structure that is using enhanced beacons, and the SignalMethod parameter value is USE_BEACON, the method described in 10.26.1 shall be initiated.

If the SignalMethod parameter value is USE_MP indicating the use of a multipurpose frame, the method described in 10.26.2 shall be initiated. The RepeatInterval parameter value should be greater than the time required to complete a transmission, acknowledgment, and possible retransmissions.

This primitive returns a Status of either SUCCESS, if the PHY parameter change notification procedure has been completed, or the appropriate Status parameter value indicating the reason for the request failure.

If the SignalMethod parameter in the request primitive is USE_BEACON and the device is a PAN coordinator in a PAN using superframe structure that is not using Enhanced Beacon frames, the MLME-PHY-OP-SWITCH.confirm primitive shall return a Status of UNSUPPORTED_FEATURE.

If the SignalMethod parameter in the request primitive is USE_BEACON and the device is not a PAN coordinator in a PAN using superframe structure, the MLME-PHY-OP-SWITCH.confirm primitive shall return a Status of INVALID_PARAMETER.

If the SignalMethod parameter value is USE_MP and the device does not support the use of multipurpose frames, the MLME-PHY-OP-SWITCH.confirm primitive shall return a Status of UNSUPPORTED_FEATURE.

If the SignalMethod parameter value is USE_MP, the RepeatCount parameter value in the request primitive is greater than zero, and the RepeatInterval value is not greater than zero, the MLME-PHY-OP-SWITCH.confirm primitive shall return with a Status of INVALID_PARAMETER.

10.26.4.3 MLME-PHY-OP-SWITCH.indication

The MLME-PHY-OP-SWITCH.indication primitive is used to indicate the reception of a multipurpose frame with a PHY Parameter Change IE and an operating mode description IE.

The semantics of this primitive are as follows:

```
MLME-PHY-OP-SWITCH.indication ( 
    DeviceAddrMode,
    DeviceAddress,
    PhyParameterList,
    TargetTime,
    NotificationTime,
    LocalTime,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-125.

On receipt of the MLME-PHY-OP-SWITCH.request primitive, the MLME initiates the PHY parameter change notification procedure, as defined in 10.26.

If the device is the PAN coordinator of a PAN using superframe structure that is using enhanced beacons, and the SignalMethod parameter value is USE_BEACON, the method described in 10.26.1 shall be initiated.

If the SignalMethod parameter value is USE_MP indicating the use of a multipurpose frame, the method described in 10.26.2 shall be initiated. The RepeatInterval parameter value should be greater than the time required to complete a transmission, acknowledgment, and possible retransmissions.

Table 10-125—MLME-PHY-OP-SWITCH.indication parameters

Name	Type	Valid range	Description
DeviceAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the device that transmitted the operating parameter switch notification command.
DeviceAddress	—	As specified by the DeviceAddrMode parameter	The address of the device that transmitted the operating parameter switch notification command.
PhyParameterList	List of PHY PIB attributes and values	As described in 12.3	A list of the PHY PIB attribute names and values representing the PHY operating parameters to be changed.
TargetTime	Integer	0–(2 ³² – 1)	The time, in microseconds, from the current time that the PHY operating parameter switch is to be carried out.
NotificationTime	Integer	0–0xffff	Value of the Notification Time field of the received PHY Parameter Change IE.
LocalTime	Integer	Implementation dependent	The time of reception of the multipurpose frame containing the IEs in the local device time reference.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

10.26.4.4 MLME-PHY-OP-SWITCH.confirm

The MLME-PHY-OP-SWITCH.confirm primitive is used to inform the next higher layer of the initiating device whether the operating parameter switching notification has completed successfully.

The semantics of this primitive are as follows:

```
MLME-PHY-OP-SWITCH.confirm ( 
    DeviceAddrMode,
    DeviceAddress,
    Status
)
```

The primitive parameters are defined in Table 10-126.

This primitive returns a Status of either SUCCESS, if the PHY parameter change notification procedure has been completed, or the appropriate Status parameter value indicating the reason for the request failure.

If the SignalMethod parameter in the request primitive is USE_BEACON and the device is a PAN coordinator in a PAN using superframe structure that is not using Enhanced Beacon frames, the MLME-PHY-OP-SWITCH.confirm primitive shall return a Status of UNSUPPORTED_FEATURE.

If the SignalMethod parameter in the request primitive is USE_BEACON and the device is not a PAN coordinator in a PAN using superframe structure, the MLME-PHY-OP-SWITCH.confirm primitive shall return a Status of INVALID_PARAMETER.

Table 10-126—MLME-PHY-OP-SWITCH.confirm parameters

Name	Type	Valid range	Description
DeviceAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode given in the request primitive.
DeviceAddress	Short address or extended address	As specified by the DeviceAddrMode parameter	The address of the device given in the request primitive.
Status	Enumeration	SUCCESS, UNSUPPORTED_FEATURE, also see 8.2.2	The status of the attempt to transmit the operating parameter switching notification command.

If the SignalMethod parameter value is USE_MP and the device does not support the use of multipurpose frames, the MLME-PHY-OP-SWITCH.confirm primitive shall return a Status of UNSUPPORTED_FEATURE.

If the SignalMethod parameter value is USE_MP, the RepeatCount parameter value in the request primitive is greater than zero, and the RepeatInterval value is not greater than zero, the MLME-PHY-OP-SWITCH.confirm primitive shall return with a Status of INVALID_PARAMETER.

10.27 MAC metrics

10.27.1 Overview of MAC metrics

The MAC will keep several metrics related to its behavior. These can also be sent to other peers by using the MAC Metrics IE or All MAC Metrics IE.

10.27.2 Nested IEs for MAC metrics

10.27.2.1 MAC Metrics IE

The MAC Metrics IE Content field shall be formatted as illustrated in Figure 10-176.

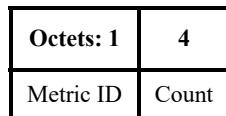


Figure 10-176—MAC Metrics IE Content field format

The Metric ID field shall be set to one of the values in Table 10-127.

Table 10-127—Metric Count IDs

Attribute name	Metric ID
<i>macCounterOctets</i>	0x01
<i>macRetryCount</i>	0x02
<i>macMultipleRetryCount</i>	0x03

Table 10-127—Metric Count IDs (continued)

Attribute name	Metric ID
<i>macTxFailCount</i>	0x04
<i>macTxSuccessCount</i>	0x05
<i>macFcsErrorCount</i>	0x06
<i>macSecurityFailure</i>	0x07
<i>macDuplicateFrameCount</i>	0x08
<i>macRxSuccessCount</i>	0x09
<i>macNackCount</i>	0x0a

10.27.2.2 All MAC Metrics IE

The All MAC Metrics IE Content field shall be formatted as illustrated in Figure 10-177.

Octets: 4	4	–	4
MAC Metric 1	MAC Metric 2	–	MAC Metric <i>n</i>

Figure 10-177—All MAC metrics IE Content field format

The MAC Metric fields contain the PIB attribute values in the order given in Table 10-127.

10.27.3 MAC constants and PIB attributes for MAC metrics

10.27.3.1 MAC performance metrics specific MAC PIB attributes

If *macMetricsEnabled* is TRUE, the MAC shall collect the metrics listed in Table 10-128.

The counters listed in Table 10-128 shall wrap to 0 when incremented beyond their maximum value. *macCounterOctets* is read only, other MAC PIB attributes in Table 10-128 are read/write and may be reset by higher layers by writing a 0 value.

The attributes *macRetryCount*, *macMultipleRetryCount*, *macTxFailCount*, and *macTxSuccessCount* relate to Data frame transmission. Each MSDU transferred into the MAC layer through the MCPS-DATA.request primitive shall increment exactly one of these four attribute counters depending on the final disposition of the frame as described in 6.6.2.

The attributes *macFcsErrorCount*, *macSecurityFailure*, *macDuplicateFrameCount*, and *macRxSuccessCount* relate to Data frame reception. Each frame received by the MAC layer shall increment at least one of these four attribute counters based on the status of the frame.

Table 10-128—Metrics-specific MAC PIB attributes

Attribute	Type	Range	Description	Default
<i>macCounterOctets</i>	Integer	1–4	The size of the MAC metrics counters in octets.	—
<i>macRetryCount</i>	Integer	$0\text{--}2^{8 \times \text{macCounterOctets}} - 1$	The number of transmitted frames that required exactly one retry before acknowledgment.	0
<i>macMultipleRetryCount</i>	Integer	$0\text{--}2^{8 \times \text{macCounterOctets}} - 1$	The number of transmitted frames that required more than one retry before acknowledgment.	0
<i>macTxFailCount</i>	Integer	$0\text{--}2^{8 \times \text{macCounterOctets}} - 1$	The number of transmitted frames that did not result in an acknowledgment after <i>macMaxFrameRetries</i> .	0
<i>macTxSuccessCount</i>	Integer	$0\text{--}2^{8 \times \text{macCounterOctets}} - 1$	The number of transmitted frames that were acknowledged successfully after the initial Data frame transmission.	0
<i>macFcsErrorCount</i>	Integer	$0\text{--}2^{8 \times \text{macCounterOctets}} - 1$	The number of frames that were discarded due to an incorrect FCS.	0
<i>macSecurityFailure</i>	Integer	$0\text{--}2^{8 \times \text{macCounterOctets}} - 1$	The number of frames that were returned from the procedure described in 9.2.4 with any Status other than SUCCESS.	0
<i>macDuplicateFrameCount</i>	Integer	$0\text{--}2^{8 \times \text{macCounterOctets}} - 1$	The number of frames that contained the same sequence number as a frame previously received.	0
<i>macRxSuccessCount</i>	Integer	$0\text{--}2^{8 \times \text{macCounterOctets}} - 1$	The number of frames that were received correctly.	0
<i>macNackCount</i>	Integer	$0\text{--}2^{8 \times \text{macCounterOctets}} - 1$	The number of transmitted frames that were acknowledged with a Time Correction IE indicating a negative acknowledgment.	0

10.28 Spectrum resource measurement (SRM)

10.28.1 General

SRM specifies the following functions and procedures in order to effectively operate wireless systems that could have heavy interferences within or outside the network:

- Spectrum resource measurements and network performance metrics, such as packet error ratio, delay, etc.
- Information elements and data structures to capture these measurements, procedures for collecting and exchanging spectrum resource measurement information with higher layers or other devices and for Transmit Power Control (TPC).

10.28.2 SRM performance metrics

10.28.2.1 Energy detection (ED)

ED capability is included in the fundamental features for PHY technologies as described in 11.2.6 (Receiver ED). In the case that SRM capabilities are supported, the ED value is represented as one octet of integer and referred to as *macEd* as shown in Table 10-144.

According to the definition in 11.2.6, the measured ED in dBm can be calculated as follows:

$$macEd = \text{Measured ED [dBm]} - (\text{the lowest receiver sensitivity [dBm]} + 10).$$

10.28.2.2 Percentage of time of failed transmissions

The percentage of time of failed transmissions feature is intended for use by a higher layer, or by a common network manager existing in a multiple wireless network environment, to aid in the estimation of propagation quality of specific links as part of a channel selection algorithm.

The output of the feature is a value for the PIB attribute *macTxFailTime*, which shall be calculated with the following equation:

$$macTxFailTime = \frac{\sum tx fail time[j]}{\sum attempted time[i]}$$

macTxFailTime is linearly scaled with 0xff representing 100%.

In this equation, *tx fail time [j]* is the time period starting at the first bit of the MPDU and stopping at the end of the last retry time out. The value of *j* is determined by the number of the failed transmissions within the Measurement time as depicted in Figure 10-178, where the first attempt on the left side is successful and not counted as *tx fail time [j]* and the second attempt on the right side is unsuccessful so that it is counted as *tx fail time [j]*. Also, *attempted time [i]* is the time when the first frame is attempted to be transmitted to the time when either it is successfully transmitted and acknowledged or it is failed to transmit by reaching *macMaxFrameRetries* times. Measurement time is defined as the duration of the requested measurement specified by the SRM Duration in Figure 10-191. By considering only the attempted time within the measurement time, the time between any two consecutive attempts, which is idle, is excluded. The accuracy for the time used in this equation shall be $\pm 100 \mu\text{s}$.

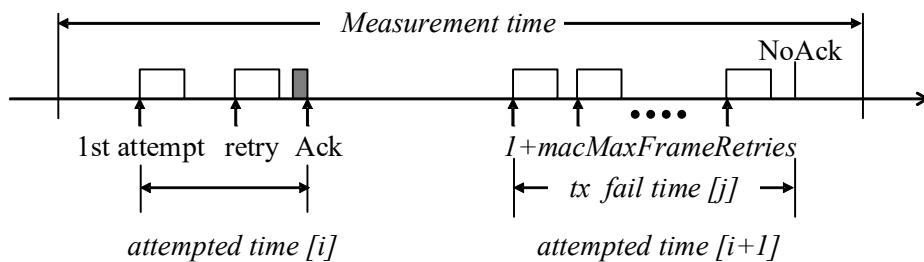


Figure 10-178—*maxTxFailTime*

10.28.2.3 Percentage of time of deferred transmissions

The percentage of time of deferred transmissions feature is intended for use by a higher layer, or by a common network manager existing in a multiple wireless network environment, to aid in the estimation of

congestion with coexisting LR-WPAN, WLAN, or other networks as part of a channel selection algorithm. The output of the feature is a value for the PIB attribute *macDeferredTxTime*, which shall be calculated with the following equation:

$$macDeferredTxTime = \frac{\sum \text{deferred period } [j]}{\sum \text{attempted time } [i]}$$

In this equation, *deferred period [j]* is the total duration of all backoff periods of all packets sent during the Measurement Time as depicted in Figure 10-179. Also, attempted time *[i]* is the time when the first frame is attempted to be transmitted to the time when it is successfully transmitted and acknowledged. Measurement time is defined as the duration of the requested measurement specified by the SRM Duration in Figure 10-191. By considering only the attempted time within the measurement time, the time between any two consecutive attempts, which is idle, is excluded. The accuracy for the time used in this equation shall be $\pm 100 \mu\text{s}$.

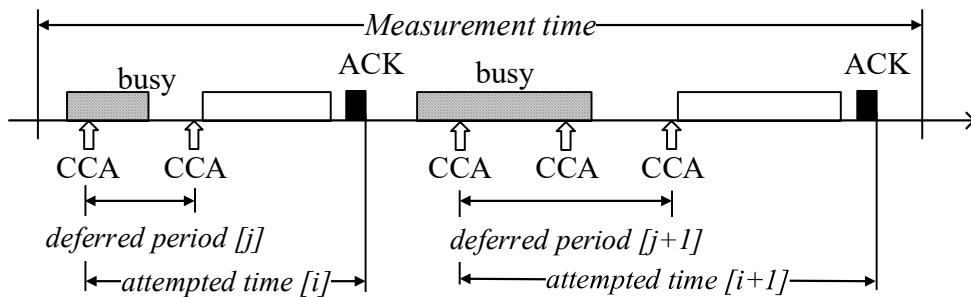


Figure 10-179—*macDeferredTxTime*

10.28.2.4 Retry histogram

The retry histogram is intended for use by the next higher layer or a common network manager existing in multiple wireless network environment, in order to optimize the utilization of spectrum resource.

The retry histogram is the histogram of the number of retries for one transmission during the measurement time. The bins range from 0 to *macMaxFrameRetries*. Retry number = 0 means that the transmission is successful without retry. Retry number = *macMaxFrameRetries* means that the transmission is failed, and it is regarded as the transmission failure. An example of a retry histogram is depicted in Figure 10-180.

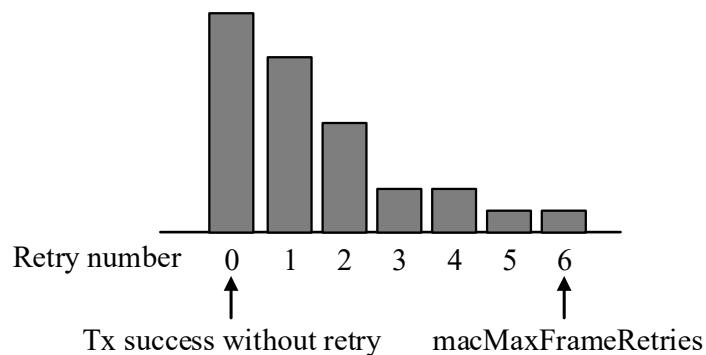


Figure 10-180—Retry histogram

10.28.2.5 Channel utilization

Channel utilization is intended for use by the next higher layer or a common network manager existing in multiple wireless network environment, in order to optimize the utilization of spectrum resource. Total channel used time for Tx and Rx over the measurement time is linearly scaled with 0xff representing 100% channel utilization.

Channel busy time is defined as follows:

- Total time of Tx and Rx of all frames including beacons and ACKs for and from this device.
- CCA time during deferred period is also added.

The accuracy for the time used shall be $\pm 100 \mu\text{s}$.

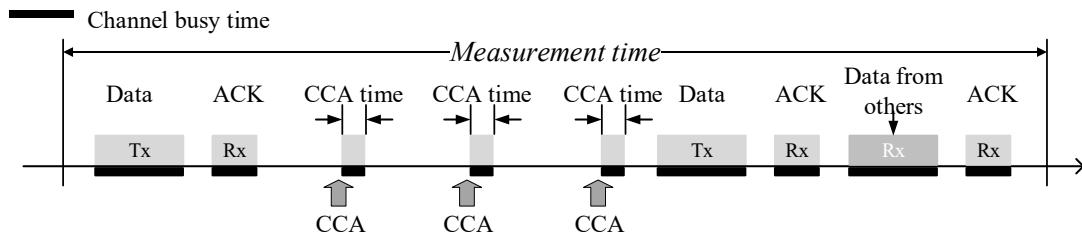


Figure 10-181—Channel utilization

10.28.2.6 Received channel power indicator (RCPI)

The received channel power indicator (RCPI) indicator defined as *macRcpi* is a measure of the received RF power in the selected channel for a received frame. RCPI value shall be equivalent to the received RF power averaged over the duration of the entire received frame. The valid range of values is 0 to 150, and shall be rounded to the nearest integer value in units of dBm. The value shall be interpreted as follows (also depicted in Figure 10-182):

- 0: Power $\leq -150 \text{ dBm}$
- 1: Power = -149 dBm
- 2: Power = -148 dBm
- and so on up to
- 150: Power $\geq -0 \text{ dBm}$
- 151–254: Reserved
- 255: Measurement not available

where

$$\text{RCPI} = \text{Integer} [\text{Power in dBm} + 150] \text{ for } 0 \text{ dBm} > \text{Power} > -150 \text{ dBm}$$

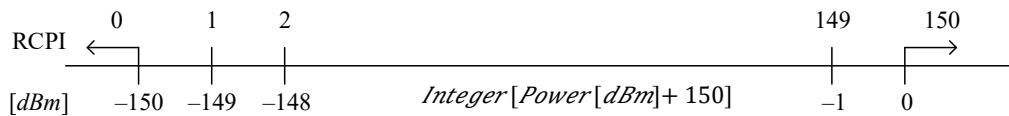


Figure 10-182—Received channel power indicator (RCPI)

10.28.2.7 Received signal noise indicator (RSNI)

Received signal noise indicator (RSNI) is intended for use by the next higher layer or a common network manager existing in a multiple wireless network environment, in order to optimize the utilization of spectrum resource.

RSNI is an indication of the signal to noise plus interference ratio of a received frame, which is defined by the ratio of the received signal power (RCPI) to the noise plus interference power (ANPI) as measured on the channel and at the antenna connector used to receive the frame. Idle power indicator (IPI) density in the specified channel is a function of time over the measurement duration where the channel is idle (CCA indicates idle and no Tx or Rx) as shown in Figure 10-183 and Table 10-129.

$$\text{IPI density} = \text{integer} \left[\frac{D_{\text{IPI}}[\mu\text{s}]}{\text{Channel idle time } [\mu\text{s}]} \times 255 \right]$$

ANPI = averaged IPI density values

ANPI is calculated by averaging IPI density (D_{IPI}) from IPI = 0 to IPI = 10.

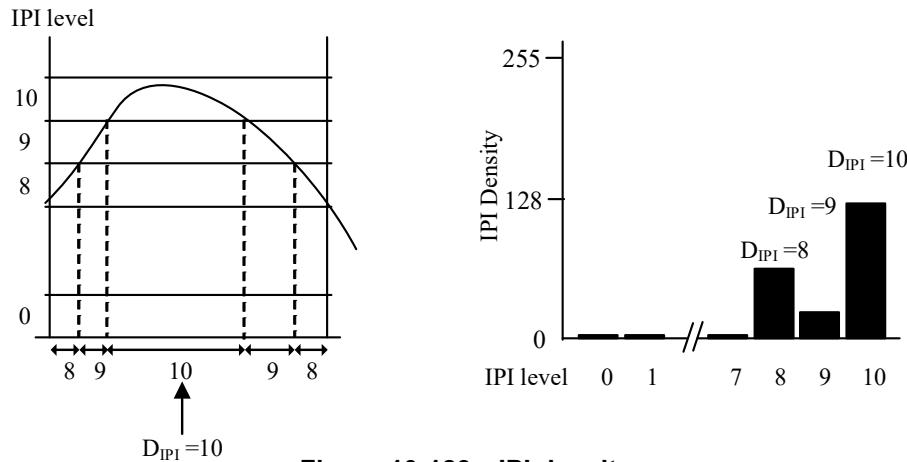


Figure 10-183—IPI density

RSNI shall be defined as $10 \times \log_{10}((\text{RCPI}_{\text{power}} - \text{ANPI}_{\text{power}})/\text{ANPI}_{\text{power}})$, where $\text{RCPI}_{\text{power}}$ and $\text{ANPI}_{\text{power}}$ indicate power domain values for RCPI and ANPI and not dB domain values. RSNI is rounded to the nearest 0.5 dB and defined over the range from -10 dB to +117 dB. RSNI shall be an 8-bit integer, having the value $\text{RSNI} = 2 \times (\text{RSNI}_{\text{dB}} + 10)$. The value 255 indicates that RSNI is not available.

RCPI, ANPI, IPI, and RSNI are specified in IEEE Std 802.11-2016 [B13]. ANPI and IPI are not a PIB attribute and are used only for calculating RSNI. The IPI value should be updated to calculate RSNI as accurately as possible. If the device operates in CCA Mode 4 or CCA capability is not used, the procedure shall return with a Status of NON_SUPPORTED.

10.28.2.8 Received signal strength indicator (RSSI)

The received signal strength indicator is intended for use by the next higher layer or a common network manager existing in a multiple wireless network environment, in order to assess the utilization of spectrum resource together with RCPI and RSNI.

RSSI is a measure of the RF power in dBm for the received packet. The RF power level at the input of the transceiver measured during the PHR and is valid after the start-of-frame delimiter (SFD) is detected. RSSI

is represented as one octet of integer as shown in Table 10-144; therefore, the minimum and maximum values are 0 (−174 dBm) and 254 (80 dBm), respectively. The value 255 is reserved. If any measured value is less than −174 dBm then the reported value shall be rounded up to −174 dBm.

10.28.2.9 Noise histogram

The noise histogram is intended for use by the next higher layer or a common network manager existing in a multiple wireless network environment, in order to optimize the utilization of spectrum resource.

The noise histogram shall be a histogram of non-IEEE 802.15 noise power in the specified channel defined as a function of time over the measurement duration when CCA indicates idle and the device is neither transmitting nor receiving a frame. The noise histogram report shall contain the IPI densities, defined in 10.28.2.7, observed in the channel for the IPI levels defined in Table 10-129. If the device operates in CCA Mode 4 or CCA capability is not used, the procedure shall return with a Status of NON_SUPPORTED.

Table 10-129—IPI definitions for noise histogram

IPI level	IPI measured power (dBm)
0	$\text{IPI} \leq -110$
1	$-110 < \text{IPI} \leq -105$
2	$-105 < \text{IPI} \leq -100$
3	$-100 < \text{IPI} \leq -95$
4	$-95 < \text{IPI} \leq -90$
5	$-90 < \text{IPI} \leq -85$
6	$-85 < \text{IPI} \leq -80$
7	$-80 < \text{IPI} \leq -75$
8	$-75 < \text{IPI} \leq -70$
9	$-70 < \text{IPI} \leq -65$
10	$-65 < \text{IPI} \leq -60$
11	$-60 < \text{IPI} \leq -55$
12	$-55 < \text{IPI}$

10.28.2.10 Average access delay

The average access delay is intended for use by the next higher layer or a common network manager existing in a multiple wireless network environment, to aid in the assessment of channel congestion with coexisting LR-WPANs, WLANs, or other networks as part of a channel selection algorithm.

The average medium access delay for transmitted frames is measured from the time the first bit of the MPDU is ready for transmission until the actual frame transmission start time in microseconds. This value is formatted as *macAverageAccessDelay* as depicted in Table 10-144. In the case of TSCH, *macTsTxOffset* can be used calculate access delay time. The average access delay is not calculated if there is no frame transmitted in the measurement time (e.g., due to the channel being busy).

10.28.2.11 MAC performance metrics specific MAC PIB attributes

If *macSrmEnabled* is TRUE, the attributes of MAC PIB defined in 10.27.3.1 shall follow the following rules. The MAC PIB attributes defined in 10.27.3.1 are also used for SRM.

By using these attributes, the packet success rate (PSR) can be calculated as follows:

$$\text{Packet success rate} = 1 - \frac{\text{macTxFailCount}}{\text{macTxSuccessCount} + \text{macRetryCount} + \text{macMultipleRetryCount} + \text{macTxFailCount}}$$

The PSR is the rate of the successfully received packets indicated by the ACK to the number of transmission attempts including the retries in the total measurement time.

The SRM Metric ID is used to indicate which metric the value in this IE represents and several IDs (e.g., *macCounterOctets*) are redefined from the MAC Metrics IE. If SRM is supported, SRM Metric ID should be used.

The Scope ID is used to indicate in which scope the metric value is valid and each scope has the following meaning and usage.

If the Scope ID is “Link”, the value is valid on the link to which the sending device is connected. The receiving device should not disseminate the information in SRM IEs to other devices.

If the Scope ID is “Path”, the value is valid on the path from the sending device to the PAN coordinator. The receiving device should send the SRM IEs to the parent device toward the PAN coordinator. The content of the SRM IEs can be modified to reflect its own situation. For example, the device may add the *macAverageAccessDelay* PIB attribute of its own to that in the SRM IE to represent the delay between the sending device and its own device and convey that value to the parent device. By performing the same process at the device on the path to the PAN coordinator, the PAN coordinator can estimate the total delay from the originating device.

NOTE—A delay has additive characteristics, while the frame loss rate has multiplicative characteristics. It depends on the parameter about how to represent the characteristics of the path, which is not specified in the document.

If the Scope ID is “Network”, the value is valid in the entire PAN. The received device should disseminate to all the neighboring device(s) by broadcast if it has not been received before. An example of using this Scope ID is to disseminate the maximum transmit power in this PAN, which is represented by *phyMaxTxPower*.

10.28.3 SRM functionality

10.28.3.1 General

When *macSrmEnabled* is set to TRUE in the coordinator and the device, the following SRM functionality shall be supported.

10.28.3.2 Signaling

The SRM IE, as defined in 10.28.5.1, is conveyed in either Enhanced Beacon frames (if supported), Multipurpose frames, or MAC Command frames. Enhanced Beacon frames are used for the devices that haven't joined the PAN yet. By receiving such Enhanced Beacon frames with SRM IEs, that device can select the most suitable PAN if multiple ones are available. Once that device has been authorized to join the PAN, SRM IEs can be conveyed on Multipurpose frames or MAC Command frames with encryption.

SRM information has the following scope of its validity:

- *Link scope*: The SRM metric(s) is/are measured on the link that the sending device is connected; thus best represent(s) the characteristics of that link.
- *Path scope*: The SRM metric(s) is/are measured on the path from the sending device to the PAN coordinator; thus best represent(s) the characteristics of that path. How it is measured is outside the scope of this specification.
- *Network scope*: The SRM metric(s) is/are measured in the entire PAN that the sending device is joining; this best represent(s) the characteristics of that PAN. How it is measured is outside the scope of this specification.

10.28.3.3 Transmit power control (TPC)

TPC is one of the effective means of enhancing the performance of WPANs. A careful setting of the operating transmit power by the wireless node offers several benefits; e.g., efficient spatial re-use of the radio spectrum and minimizes interference. At the time of joining the network, the maximum transmit power that the device shall abide by is notified by the adjacent devices that are already in the network via the beacon frame or association response frame. After joining the network, the device can specify the transmit power for the following communication types:

- Broadcast communication (e.g., in the scan process) by setting *phyBroadcastTxPower*.
- Unicast communication with any device (e.g., when a specific communication quality is required for an individual communication or in order to reduce the interference to other devices) by setting *phyUnicastTxPower*.
- Unicast communication with a specific peer device by setting *phyPeersTxPower*.

The transmit power described above shall not exceed the maximum transmit power, as *phyMaxTxPower* defined in Table 12-2. If the TX power is limited for a device in the PAN, where CSMA-CA is employed, it should be limited to the same value for all devices in the PAN to enable the CSMA-CA algorithm to work correctly.

10.28.3.4 SRM Request/Response

SRM Request/Response flows for getting PIB information are depicted in Figure 10-184. The higher layer on the receiver side may be involved as shown in the dotted box if the decision needs to be made by the higher layer, but this is not always the case.

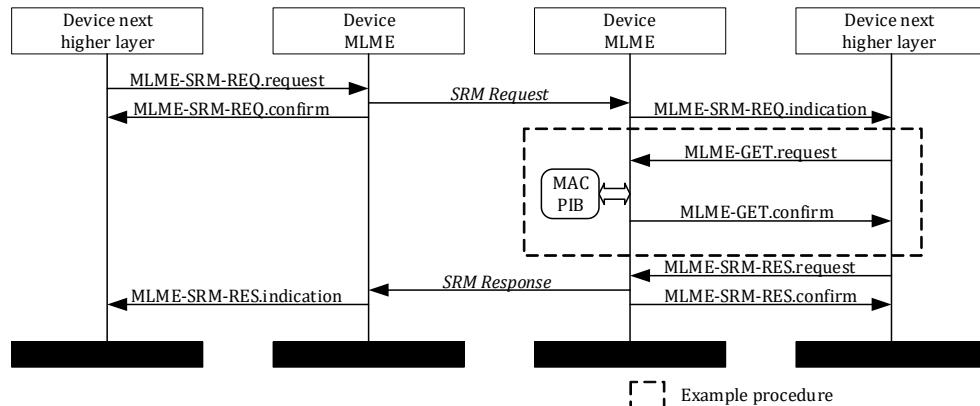
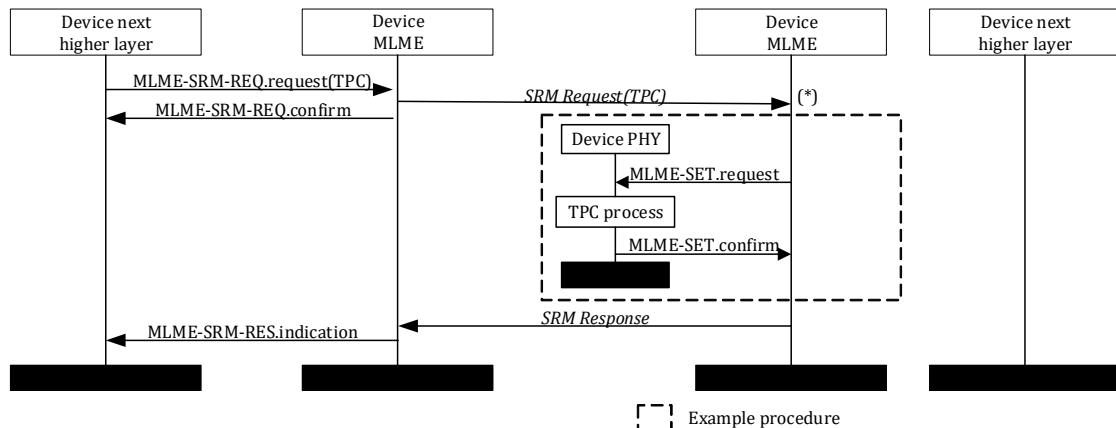


Figure 10-184—SRM Request/Response flows for getting PIB information

SRM Request/Response flows for setting PIB information (e.g., TPC) are depicted in Figure 10-185. The lower layer may be involved as shown in the dotted box if the requested procedure needs to be taken by the lower layer, but this is not always the case.



(*) Depending on the application or use case, it is also possible that the MAC layer of the recipient of SRM Request notifies the higher layer of its reception by MLME-SRM-RES.indication and the higher layer triggers MLME-SET to control the lower layer.

Figure 10-185—SRM Request/Response flows for setting PIB information

10.28.3.5 SRM Report

SRM Report flows are depicted in Figure 10-186. The SRM Report command is sent from a device to the PAN coordinator periodically or based on some event.

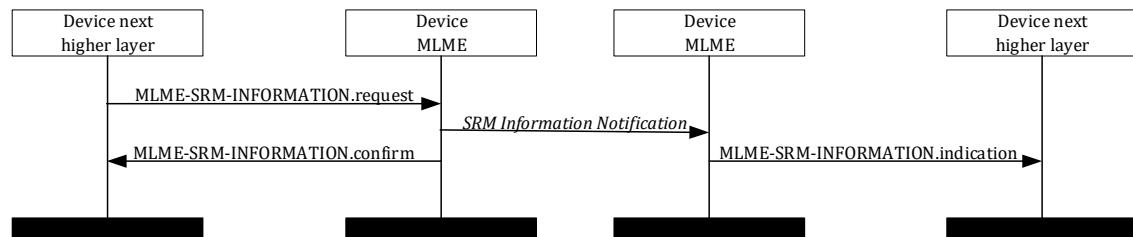


Figure 10-186—SRM Report flow

10.28.3.6 SRM Information

SRM Information flows are depicted in Figure 10-187. SRM Information Notification can be sent by the Enhanced Beacon, MAC command, or multipurpose frame, which is specified by the higher layer. If AckedConfirm described in Table 10-135 is set to TRUE in the MLME-SRM-INFORMATION.request primitive, MLME-SRM-INFORMATION.confirm is returned when the SRM Information Notification is

acknowledged. If AckedConfirm is set to FALSE, MLME-SRM-INFORMATION.confirm is returned immediately after the SRM Information Notification is successfully transmitted.

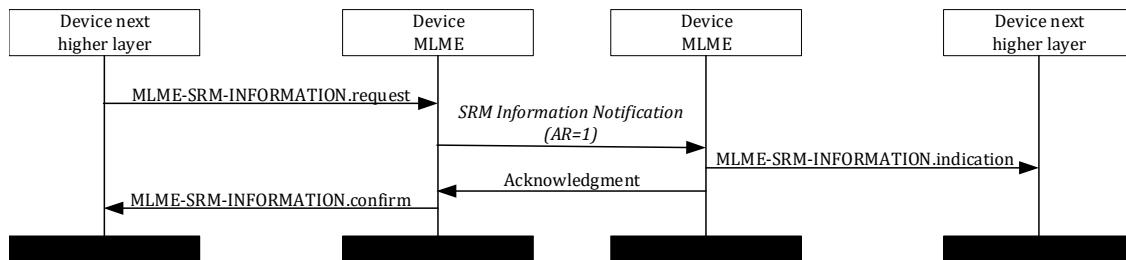


Figure 10-187—SRM Information flow with waiting for acknowledgment

10.28.4 Using Link Margin IE

A device may include a Link Margin IE within an enhanced acknowledgment. The Link Margin IE shall only be transmitted as part of an Enh-Ack frame.

If a device receives an Enh-Ack frame containing a Link Margin IE, it may adjust its transmit power within its power control range in all following GTS transmissions directed to the originating device. The transmit power control can ignore the Link Margin IE when the device is transmitting non-GTS frames. If a device supports more than one data rate, a higher layer may use the information contained in the Link Margin IE to determine that the link margin is sufficient to support a higher data rate. The Link Margin IE is described in 10.28.6.1.

If an acknowledgment for a transmission to a particular device is not received, the transmit power for transmissions to that device may be increased for the next transmission attempt.

The algorithm that controls the transmission of the Link Margin IE and the algorithm that acts on the reception of the Link Margin IE are outside the scope of this standard.

If the security level, as described in 9.4.2.2, of the incoming Enh-Ack frame containing the Link Margin IE is lower than that of the frame being acknowledged, then the Link Margin IE shall be ignored.

10.28.5 Header IEs for SRM

10.28.5.1 SRM IE

The SRM IE field shall be formatted as illustrated in Figure 10-188. The format of SRM Metric ID and Scope ID are defined in Table 10-130 and Table 10-131, respectively. Type and range for the Content field shall be defined in corresponding attribute in Table 10-144.

Bits: 0–5	6–7	Octet: 0–126
SRM Metric ID	Scope ID	Content

Figure 10-188—Format of SRM Metric IE

Table 10-130—SRM Metric ID

Attribute name	SRM Metric ID
<i>macEd</i>	0
<i>macTxFailTime</i>	1
<i>macTxDeferredTime</i>	2
<i>macRetryHistogram</i>	3
<i>macChannelUtilization</i>	4
<i>macRpri</i>	5
<i>macRsni</i>	6
<i>macRssi</i>	7
<i>macNoiseHistogram</i>	8
<i>macFrameErrorCount</i>	9
<i>macCounterOctets</i>	10
<i>macRetryCount</i>	11
<i>macMultipleRetryCount</i>	12
<i>macTxFailCount</i>	13
<i>macTxSuccessCount</i>	14
<i>macFcsErrorCount</i>	15
<i>macSecurityFailure</i>	16
<i>macDuplicateFrameCount</i>	17
<i>macRxSuccessCount</i>	18
<i>macNackCount</i>	19
<i>macDeferredTxCount</i>	20
<i>macAverageBufferUtilization</i>	21
<i>macMaximumBufferUtilization</i>	22
<i>macTxFragmentCount</i>	23
<i>macRxFragmentCount</i>	24
<i>macTxMulticastCount</i>	25
<i>macRxMulticastCount</i>	26
<i>macAverageAccessDelay</i>	27
Reserved	28
<i>macSrmChannelNumber</i>	29
<i>macSrmRxAddrMode</i>	30
<i>macSrmRxDeviceAddress</i>	31
Reserved	32–63

Table 10-131—SRM Scope ID

Measured range	Scope ID
Link	0
Path	1
Network	2
Reserved	3

10.28.6 Nested IEs for SRM

10.28.6.1 Link Margin IE

The Link Margin IE is optional and shall only be used in Enh-Ack frames. The Link Margin IE Content field shall be formatted as illustrated in Figure 10-189.

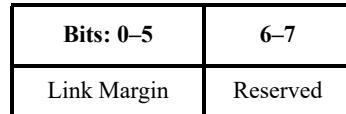


Figure 10-189—Link Margin IE Content field format

The Link Margin field shall be set to the available link margin, represented as a two's-complement number, defining the link margin in decibels with a range from –31 dB to 32 dB, in steps of 1 dB. The Link Margin field shall comply with the following equation:

$$\text{Link Margin} = S_{\text{received}} - S_{\text{sensitivity}}$$

where

S_{received} is the received power, in dBm, during a frame as measured in the receiver.

$S_{\text{sensitivity}}$ is the lowest input power required by the receiver, for the PHY that was used during the received frame. The conditions at which the lowest input power is determined are as follows: the packet error rate (PER) is 1%, and each packet in the PER measurement has a PSDU containing random data with a length of 250 octets.

The accuracy of S_{received} and $S_{\text{sensitivity}}$ is left to the implementer.

For example, if a frame is received with $S_{\text{received}} = -72$ dBm and the received sensitivity ($S_{\text{sensitivity}}$) is –102 dBm, then the subsequent Enh-Ack frame may have the Link Margin IE included with the Link Margin field set to 30 dB.

10.28.7 MAC commands for SRM

10.28.7.1 SRM Request command

The AR field shall be set to one. The Frame Version field shall be set to two.

The SRM Request command Content field shall be formatted as illustrated in Figure 10-190.

Bits:0–5	6–7	Octets:1	variable
SRM Metric ID	Scope ID	SRM Token	Measurement Information

Figure 10-190—SRM Request command Content field format

The SRM Metric ID and the Scope ID shall be formatted as described in Table 10-130 and Table 10-131, respectively.

The SRM Token shall be set to the value in SrmToken as defined in Table 10-138 of the MLME-SRM-REQ.request primitive. The value is unique among outstanding SRM Request frames from the same source device.

The Measurement Information field shall be formatted as illustrated in Figure 10-191.

Bits: 0	1	2	3	4	5–15	Octets:0/1	0/4	0/1	0/2	0/2
Start Time Present	SRM Duration Present	Reserved Present	Channel Number Present	Link Handle Present	Reserved	Start Time	SRM Duration	Reserved	Channel Number	Link Handle

Figure 10-191—Measurement Information field format

The Start Time Present field shall be set to one if the Start Time is present and shall be set to zero if the Start Time is not present. If Start Time is not present or is set to zero, the measurement is started immediately.

The SRM Duration Present field shall be set to one if the SRM Duration is present and shall be set to zero if the SRM Duration is not present.

The Reserved Present shall be set to one if the Reserved field is present and shall be set to zero if the Reserved field is not present.

The Channel Number Present field shall be set to one if the Channel Number is present and shall be set to zero if the Channel Number is not present.

The Start Time field indicates the time in at which the measurement is started. The actual start time may be aligned with the start time of the closest timeslot. The measuring device shall start the measurement after a delay specified as the Start Time, as specified in seconds, at the time of receiving the request. If no local clock is available or the Start Time Present field is set to zero, the measuring device shall start the measurement as soon as practical after receiving the request and ignore the delay specified as part of the Start Time. When requesting the current value of an SRM metric, the SRM Duration and Channel Number are omitted.

The SRM Duration field in units of timeslots indicates the duration during which the measurement is to be performed. The unit of a timeslot equals to 1 ms. If SRM Duration is not present, then Start Time is ignored and current metric is requested.

The Channel Number field indicates the channel number on which the measurement is to be performed. If Channel Number is not present, then current channel number is used.

The Link Handle field, described in Table 10-138, indicates the link on which the measurement is to be performed. If Link Handle is not present, then current link handle is used.

10.28.7.2 SRM Response command

The AR field shall be set to one. The Frame Version field shall be set to two.

The SRM Response command Content field shall be formatted as illustrated in Figure 10-192.

Bits:0–5	6–7	Octets:1	1	Octets: variable	variable
SRM Metric ID	Scope ID	SRM Token	SRM Status	Measured Device Information	Attribute Value

Figure 10-192—SRM Response command Content field format

The SRM Metric ID and the Scope ID values are defined in Table 10-130 and Table 10-131, respectively.

The SRM Token field shall be set to SRM Token in the corresponding SRM Request element.

The SRM Status field shall be formatted as illustrated in Figure 10-193.

Status	Description
0	Success
1	Not Supported
2	Rejected
3–15	Reserved

Figure 10-193—SRM Status field format

The Measured Device Information field shall be formatted as illustrated in Figure 10-194.

Bits:0–1	2–7	Octets:2/8
Address Mode	Reserved	Device Address

Figure 10-194—Measured Device Information field format

The Address Mode field, which shall be set to one of the values given in Table 7-3, indicates the address mode of the device that conducted the measurement.

The Device Address field, which shall be set to the short address or extended address according to the Address Mode field, indicates the address of the device that conducted the measurement.

The Attribute Value field contains the PIB attribute value defined in Table 10-144.

10.28.7.3 SRM Report command

The AR field shall be set to one. The Frame Version field shall be set to two.

The SRM Report command Content field shall be formatted as illustrated in Figure 10-195.

Bits:0–5	6–7	Octets:1	variable	variable
SRM Metric ID	Scope ID	SRM Token	Measurement Information	Attribute Value

Figure 10-195—SRM Report command Content field format

The SRM Metric ID and the Scope ID shall be formatted as described in Table 10-130 and Table 10-131, respectively.

The SRM Token field shall be set to the SRM Token in the corresponding the SRM Request element. If the SRM Report element is being sent autonomously, then the SRM Token is set to zero.

The Measurement Information field shall be formatted as illustrated in Figure 10-191.

The Attribute Value field contains the PIB attribute value defined in Table 10-144.

10.28.7.4 SRM Information command

The AR field shall be set to one. The Frame Version field shall be set to two.

The SRM Information command Content field shall be formatted as illustrated in Figure 10-196.

Bit:0–5	6–7	Octet:1	variable	variable
SRM Metric ID	Scope ID	SRM Token	Measurement Information	Attribute Value

Figure 10-196—SRM Information command Content field format

The SRM Metric ID and the Scope ID values are defined in Table 10-130 and Table 10-131, respectively.

The SRM Token field shall be set to the SRM Token in the corresponding the SRM Request element. If the SRM Information is being sent autonomously, then the SRM Token is set to zero.

The Measurement Information field shall be formatted as illustrated in Figure 10-191.

The Attribute Value field contains the PIB attribute value defined in Table 10-144.

10.28.8 MAC management service primitives for SRM

10.28.8.1 General

These primitives are used by a device when PIB attribute *macSRMcapable* set to TRUE.

10.28.8.2 MLME-SRM-REPORT

10.28.8.2.1 MLME-SRM-REPORT.request

The MLME-SRM-REPORT.request primitive is used by a device to send an SRM Report command.

The semantics of this primitive are as follows:

```
MLME-SRM-REPORT.request ( 
    SrmHandle,
    DeviceAddrMode,
    DeviceAddress,
    PayloadList,
    SrmMetricId,
    Scopeld,
    SrmToken,
    StartTime,
    Duration,
    ChannelInfo,
    LinkHandle,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-132.

Table 10-132—MLME-SRM-REPORT.request parameters

Name	Type	Valid range	Description
SrmHandle	Integer	0x00–0xff	An identifier that can be used to refer to the particular primitive transaction; used to match a confirm primitive with the corresponding request.
DeviceAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the device to which SRM report is transferred.
DeviceAddress	Short address or extended address	As specified by the DeviceAddrMode parameter	The address of the device to which SRM report is transferred.
PayloadList	Set of payload IEs as described in 7.4.3	—	As defined in Table 8-30.

Table 10-132—MLME-SRM-REPORT.request parameters (continued)

Name	Type	Valid range	Description
SrmMetricId	Integer	0x00–0x3f	The SrmMetricId as defined in 10.28.5.1.
ScopeId	Enumeration	LINK, PATH, NETWORK	The scope of the SRM operation as defined in 10.28.5.1.
SrmToken	Integer	0x01–0xff	SrmToken when sending SRM Report command.
StartTime	Unsigned Integer	0x00–0xff	The time at which the requested measurement should be started as specified in 10.28.7.1. If start time is not used, this parameter shall be set to 0xff.
Duration	Integer	0x0000–0xffff	The duration over which the requested measurement should be measured as specified in 10.28.7.1. If duration is not used, this parameter shall be set to 0xffff.
ChannelInfo	Channel information structure as defined in 11.1.3.1	Any valid channel	The channel on which the measurement is to be executed. If channel number is not used, this parameter shall be set to null.
LinkHandle	Integer	0x0000–0xffff	The identifier of Link specified by <i>macLinkHandle</i> in Table 10-18. If Link is not used, LinkHandle shall be set to 0xffff.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

When the MLME-SRM-REPORT.request is issued by the next higher layer of a device, the MLME of the device acknowledges it by sending back an MLME-SRM-REPORT.confirm primitive with a Status code. The MAC then gets the measurement value indicated by SrmMetricId, generates SRM Report command, and attempts to send it to the specified destination device as DeviceAddress.

10.28.8.2.2 MLME-SRM-REPORT.indication

The MLME-SRM-REPORT.indication primitive indicates the reception of an SRM Report command, Enh-Ack frame or Multipurpose frame. The semantics of this primitive are as follows:

```
MLME-SRM-REPORT.indication ( 
    DeviceAddrMode,
    DeviceAddress,
    PayloadList,
    SrmMetricId,
    ScopeId,
    SrmToken,
    StartTime,
    Duration,
    ChannelInfo,
    LinkHandle,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-133.

Table 10-133—MLME-SRM-REPORT.indication parameters

Name	Type	Valid range	Description
DeviceAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the device that sent the SRM Report.
DeviceAddress	Short address or extended address	As specified by the DeviceAddrMode parameter	The address of the device that sent the SRM Report.
PayloadList	Set of payload IEs as described in 7.4.3	—	As defined in Table 8-32.
SrmMetricId	Integer	0x00–0x3f	The SrmMetricId as defined in 10.28.5.1.
ScopeId	Enumeration	LINK, PATH, NETWORK	The scope of the SRM operation as defined in 10.28.5.1.
SrmToken	Integer	0x01–0xff	SrmToken field of the received SRM Report command.
StartTime	Unsigned Integer	0x00–0xff	The time at which the requested measurement should be started as specified in 10.28.7.1. If start time is not used, this parameter shall be set to 0xff.
Duration	Integer	0x0000–0xffff	The duration over which the requested measurement should be measured as specified in 10.28.7.1. If duration is not used, this parameter shall be set to 0xffff.

Table 10-133—MLME-SRM-REPORT.indication parameters (continued)

Name	Type	Valid range	Description
ChannelInfo	Channel information structure as defined in 11.1.3.1	Any valid channel	The channel on which the measurement is to be executed. If channel number is not used, this parameter shall be set to null.
LinkHandle	Integer	0x0000–0xffff	The identifier of Link specified by <i>macLinkHandle</i> in Table 10-18. If Link is not used, LinkHandle shall be set to 0xffff.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

10.28.8.2.3 MLME-SRM-REPORT.confirm

The MLME-SRM-REPORT.confirm primitive is generated by the MLME and issued to its next higher layer in response to an MLME-SRM-REPORT.request primitive.

The semantics of this primitive are as follows:

```
MLME-SRM-REPORT.confirm      (
    SrmHandle,
    Status
)
```

The primitive parameters are defined in Table 10-134.

Table 10-134—MLME-SRM-REPORT.confirm parameters

Name	Type	Valid range	Description
SrmHandle	Integer	0x00–0xff	An identifier that can be used to refer to the particular primitive transaction, used to match a confirm primitive with the corresponding request.
Status	Enumeration	SUCCESS, also see 8.2.2	The result of the attempt to send SRM Report.

The MLME-SRM-REPORT.confirm primitive returns a Status value defined in Table 10-134.

10.28.8.3 MLME-SRM-INFORMATION

10.28.8.3.1 MLME-SRM-INFORMATION.request

The MLME-SRM-INFORMATION.request is issued to request MAC to start sending SRM information. The MLME then generates SRM Information Command and attempts to send it to the specified destination device.

The semantics of this primitive are as follows:

```
MLME-SRM-INFORMATION.request (
    SrmHandle,
    DeviceAddrMode,
    DeviceAddress,
    PayloadIdleList,
    SrmMetricId,
    ScopeId,
    SrmToken,
    StartTime,
    Duration,
    ChannelInfo,
    LinkHandle,
    SignalMethod,
    AckedConfirm,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-135.

Table 10-135—MLME-SRM-INFORMATION.request parameters

Name	Type	Valid range	Description
SrmHandle	Integer	0x00–0xff	An identifier that can be used to refer to the particular primitive transaction; used to match a confirm primitive with the corresponding request.
DeviceAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the device, to which SRM report is transferred.
DeviceAddress	Short address or extended address	As specified by the DeviceAddrMode parameter	The address of the device to which SRM report is transferred.
PayloadIdleList	Set of payload IEs as described in 7.4.3	—	As defined in Table 8-30.
SrmMetricId	Integer	0x00–0x3f	The SrmMetricId as defined in 10.28.5.1.
ScopeId	Enumeration	LINK, PATH, NETWORK	The scope of the SRM operation as defined in 10.28.5.1.
SrmToken	Integer	0x01–0xff	SrmToken when sending SRM Information command.
StartTime	Unsigned Integer	0x00–0xff	The time at which the requested measurement should be started as specified in 10.28.7.1.
Duration	Integer	0x0000–0xffff	The duration over which the requested measurement should be measured.

Table 10-135—MLME-SRM-INFORMATION.request parameters (continued)

Name	Type	Valid range	Description
ChannelInfo	Channel information structure as defined in 11.1.3.1	Any valid channel	The channel on which the measurement is to be executed.
LinkHandle	Integer	0x0000–0xffff	The identifier of Link specified by <i>macLinkHandle</i> in Table 10-18. If Link is not used, LinkHandle shall be set to 0xffff.
SignalMethod	Enumeration	USE_BEACON, USE_CMD, USE_MP	The method to be used to signal intended primitive among the Enhanced Beacon, MAC command, or multipurpose frame.
AckedConfirm	Boolean	TRUE, FALSE	Set to TRUE if Acknowledgment is required for MLME-SRM-INFORMATION.confirm.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

The MAC gets the measurement value indicated by SrmMetricId, and generates SRM Information command. If SignalMethod is USE_BEACON, then the MAC will include SRM IE in the enhanced beacon, and AckedConfirm has to be FALSE. If SignalMethod is USE_CMD or USE_MP, then AckedConfirm specifies whether the acknowledgments are requested or not.

10.28.8.3.2 MLME-SRM-INFORMATION.indication

The MLME-SRM-INFORMATION.indication primitive is generated by the MAC sublayer and issued to the next higher layer on receipt of an SRM Information request.

The semantics of this primitive are as follows:

```
MLME-SRM- INFORMATION.indication(
    DeviceAddrMode,
    DeviceAddress,
    PayloadIeList,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-136.

SRM IE, which contains the SRM Metric ID, the Scope ID, and the Content, shall be included in PayloadIeList.

Table 10-136—MLME-SRM-INFORMATION.indication parameters

Name	Type	Valid range	Description
DeviceAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the device that sent the SRM Information Notification message.
DeviceAddress	Short address or extended address	As specified by the DeviceAddrMode parameter	The address of the device that sent the SRM Information Notification message.
PayloadIeList	Set of payload IEs as described in 7.4.3	—	As defined in Table 8-32.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

10.28.8.3.3 MLME-SRM-INFORMATION.confirm

The MLME-SRM-INFORMATION.confirm primitive is generated by the MLME and issued to its next higher layer in response to an MLME-SRM-INFORMATION.request primitive.

The semantics of this primitive are as follows:

```
MLME-SRM-INFORMATION.confirm ( 
    SrmHandle,
    Status
)
```

The primitive parameters are defined in Table 10-137.

Table 10-137—MLME-SRM-INFORMATION.confirm parameter

Name	Type	Valid range	Description
SrmHandle	Integer	0x00–0xff	An identifier that can be used to refer to the particular primitive transaction; used to match a confirm primitive with the corresponding request.
Status	Enumeration	SUCCESS, also see 8.2.2	The result of the attempt to send SRM Information.

If the SignalMethod parameter in the request primitive is USE_BEACON and the device is a PAN coordinator in a PAN using superframe structure that is not using Enhanced Beacon frames, the MLME-SRM-INFORMATION.confirm primitive shall return a Status of UNSUPPORTED_FEATURE.

The MLME-SRM-INFORMATION.confirm primitive is generated by the MLME and issued to its next higher layer in response to an MLME-SRM-INFORMATION.request primitive. The MLME-SRM-INFORMATION.confirm primitive returns a Status value defined in Table 10-137.

10.28.8.4 MLME-SRM-REQ

10.28.8.4.1 MLME-SRM-REQ.request

The MLME-SRM-REQ.request primitive is used by a device to request that a device start collecting SRM information.

The semantics of this primitive are as follows:

```
MLME-SRM-REQ.request      (
    SrmHandle,
    DeviceAddrMode,
    DeviceAddress,
    PayloadList,
    SrmMetricId,
    ScopeId,
    SrmToken,
    StartTime,
    Duration,
    ChannelInfo,
    LinkHandle,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-138.

Table 10-138—MLME-SRM-REQ.request parameters

Name	Type	Valid range	Description
SrmHandle	Integer	0x00–0xff	An identifier that can be used to refer to the particular primitive transaction; used to match a confirm primitive with the corresponding request.
DeviceAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the device being instructed to execute SRM operation.
DeviceAddress	Short address or extended address	As specified by the DeviceAddrMode parameter	The address of the device being instructed to execute SRM operation.
PayloadList	Set of payload IEs as described in 7.4.3	—	As defined in Table 8-30.
SrmMetricId	Integer	0x00–0x3f	The SRM Metric ID as defined in 10.28.5.1.
ScopeId	Enumeration	LINK, PATH, NETWORK	The scope of the SRM operation as defined in 10.28.5.1.
SrmToken	Integer	0x01–0xff	A unique number to identify the SRM request element between the sender and the receiver.
StartTime	Unsigned Integer	0x00–0xff	The time at which the requested measurement should be started as specified in 10.28.7.1. If Start Time is not used, this parameter shall be set to 0xff.
Duration	Integer	0x0000–0xffff	The duration over which the requested measurement should be measured as specified in 10.28.7.1. 0xffff is a reserved number, and if Duration is not used, this parameter shall be set to 0xffff.

Table 10-138—MLME-SRM-REQ.request parameters (continued)

Name	Type	Valid range	Description
ChannelInfo	Channel information structure as defined in 11.1.3.1	Any valid channel	The channel on which the measurement is to be executed. If Channel Number is not used, this parameter shall be set to null.
LinkHandle	Integer	0x0000–0xffff	The identifier of Link specified by <i>macLinkHandle</i> in Table 10-18. If Link is not used, LinkHandle shall be set to 0xffff.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

On receipt of MLME-SRM-REQ.request primitive by a device, the MLME of the device attempts to generate an SRM Request command as described in 10.28.7.1 with the information contained in this primitive, and if successful, sends it to the destination device according to the DstAddr parameter.

10.28.8.4.2 MLME-SRM-REQ.indication

This MLME-SRM-REQ.indication primitive is generated to indicate the reception of SRM Request command.

The semantics of this primitive are as follows:

```
MLME-SRM-REQ.indication (DeviceAddrMode, DeviceAddress, PayloadList, SrmToken, StartTime, Duration, ChannelInfo, LinkHandle, SecurityParams)
```

The primitive parameters are defined in Table 10-139.

Table 10-139—MLME-SRM-REQ.indication parameters

Name	Type	Valid range	Description
DeviceAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the device requesting to execute SRM operation.
DeviceAddress	Short address or extended address	As specified by the DeviceAddrMode parameter	The address of the device requesting to execute SRM operation.
PayloadList	Set of payload IEs as described in 7.4.3	—	As defined in Table 8-32.

Table 10-139—MLME-SRM-REQ.indication parameters (continued)

Name	Type	Valid range	Description
SrmToken	Integer	0x01–0xff	SrmToken of the incoming SRM Report command.
StartTime	Unsigned Integer	0x00–0xff	The time at which the requested measurement should be started as specified in 10.28.7.1.
Duration	Integer	0x0000–0xffff	The duration over which the requested measurement should be measured.
ChannelInfo	Channel information structure as defined in 11.1.3.1	Any valid channel	The channel on which the measurement is to be executed.
LinkHandle	Integer	0x0000–0xffff	The identifier of Link specified by <i>macLinkHandle</i> in Table 10-18. If Link is not used, LinkHandle shall be set to 0xffff.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

The MLME-SRM-REQ.indication primitive is generated by the MAC sublayer and issued to the next higher layer on receipt of an SRM Request command, which then takes a designated action as described in 10.28.3.4.

The role of SrmToken with source address, which is locally unique, in MLME-SRM.response is to match the corresponding Response.

10.28.8.4.3 MLME-SRM-REQ.confirm

The MLME-SRM-REQ.confirm primitives reports the results of the MLME-SRM-REQ.request.

The semantics of this primitive are as follows:

```
MLME-SRM-REQ.confirm      (
    SrmHandle,
    Status
)
```

The primitive parameters are defined in Table 10-140.

Table 10-140—MLME-SRM-REQ.confirm parameters

Name	Type	Valid range	Description
SrmHandle	Integer	0x00–0xff	The identifier of the corresponding MLME-SRM-REQ.request primitive.
Status	Enumeration	SUCCESS, see also 8.2.2	The status of the SRM attempt.

The MLME-SRM-REQ.confirm primitive returns a Status of either SUCCESS, indicating the MAC sublayer has sent the SRM request, or the appropriate error code.

10.28.8.5 MLME-SRM-RES

10.28.8.5.1 MLME-SRM-RES.request

This MLME-SRM-RES.request primitives is used to initiate a response to an MLME-SRM-REQ.indication primitive.

The semantics of this primitive are as follows:

```
MLME-SRM-RES.request      (
    SrmHandle,
    DeviceAddrMode,
    DeviceAddress,
    PayloadList,
    SrmToken,
    SrmMetricId,
    Scopeld,
    StartTime,
    Duration,
    ChannelInfo,
    LinkHandle,
    MeasuredDeviceAddrMode,
    MeasuredDeviceAddress,
    SrmStatus,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-141, which are provided by the device next higher layer.

Table 10-141—MLME-SRM-RES.request parameter

Name	Type	Valid range	Description
SrmHandle	Integer	0x00–0xff	An identifier that can be used to refer to the particular primitive transaction; used to match an MLME-SRM-RES.request with corresponding MLME-SRM-RES.confirm.
DeviceAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the device requesting to execute SRM operation.
DeviceAddress	Short address or extended Address	As specified by the DeviceAddrMode parameter	The address of the device requesting to execute SRM operation.
PayloadList	Set of payload IEs as described in 7.4.3	—	The payload IEs, excluding Termination IEs, that are provided by the device next higher layer. If empty, then no payload IEs were included. As defined in Table 8-30.

Table 10-141—MLME-SRM-RES.request parameter (continued)

Name	Type	Valid range	Description
SrmToken	Integer	0x01–0xff	An identifier used to match the SRM request with the corresponding SRM response.
SrmMetricId	Integer	0x00–0x3f	The SrmMetricId as defined in 10.28.5.1.
ScopeId	Enumeration	LINK, PATH, NETWORK	The scope of the SRM operation as defined in 10.28.5.1.
StartTime	Unsigned Integer	0x00–0xff	The time at which the requested measurement should be started as specified in 10.28.7.1. If start time is not used, this parameter shall be set to 0xff.
Duration	Integer	0x0000–0xffff	The duration over which the requested measurement should be measured as specified in 10.28.7.1. If duration is not used, this parameter shall be set to 0xffff.
ChannelInfo	Channel information structure as defined in 11.1.3.1	Any valid channel	The channel on which the measurement is to be executed. If channel number is not used, this parameter shall be set to null.
LinkHandle	Integer	0x0000–0xffff	The identifier of Link specified by <i>macLinkHandle</i> in Table 10-18. If Link is not used, LinkHandle shall be set to 0xffff.
MeasuredDevice AddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the device, for which the measurement was executed.
MeasuredDevice Address	Short address or extended address	As specified by the DeviceAddrMode parameter	The address of the device, for which the measurement was executed.
SrmStatus	Enumeration	SUCCESS, NON_SUPPORTED, REJECTED	The status of the SRM attempt.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

When the MLME-SRM-RES.request is received by the MAC, then it gets the measurement value indicated by SrmMetricId, and the SRM Response command defined in 10.28.7.2 is generated and sent to the originating device.

10.28.8.5.2 MLME-SRM-RES.indication

The MLME-SRM-RES.indication primitive is used to report the SRM Response command.

The semantics of this primitive are as follows:

```
MLME-SRM-RES.indication ( SrmToken,
                           DeviceAddrMode,
                           DeviceAddress,
                           PayloadIdleList,
                           SrmMetricId,
                           ScopeId,
                           StartTime,
                           Duration,
                           ChannelInfo,
                           LinkHandle,
                           MeasuredDeviceAddrMode,
                           MeasuredDeviceAddress,
                           SrmStatus,
                           SecurityParams
                         )
```

The primitive parameters are defined in Table 10-142.

Table 10-142—MLME-SRM-RES.indication parameters

Name	Type	Valid range	Description
SrmHandle	Integer	0x00–0xff	An identifier that can be used to refer to the particular primitive transaction; used to match an indication primitive with the corresponding MLME-SRM-REQ.request.
DeviceAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the device requesting to execute SRM operation.
DeviceAddress	Short address or extended address	As specified by the DeviceAddrMode parameter	The address of the device requesting to execute SRM operation.
PayloadIdleList	Set of payload IEs as described in 7.4.3	—	The SRM-related payload IEs, excluding Termination IEs, that were included in the frame. If empty, then no payload IEs are included.
SrmMetricId	Integer	0x00–0x3f	The SrmMetricId as defined in 10.28.5.1.
ScopeId	Enumeration	LINK, PATH, NETWORK	The scope of the SRM operation as defined in 10.28.5.1.

Table 10-142—MLME-SRM-RES.indication parameters (continued)

Name	Type	Valid range	Description
StartTime	Unsigned Integer	0x00–0xff	The time at which the requested measurement should be started as specified in 10.28.7.1. If start time is not used, this parameter shall be set to 0xff.
Duration	Integer	0x0000–0xffff	The duration over which the requested measurement should be measured as specified in 10.28.7.1. If duration is not used, this parameter shall be set to 0xffff.
ChannelInfo	Channel information structure as defined in 11.1.3.1	Any valid channel	The channel on which the measurement is to be executed. If channel number is not used, this parameter shall be set to null.
LinkHandle	Integer	0x0000–0xffff	The identifier of Link specified by <i>macLinkHandle</i> in Table 10-18. If Link is not used, LinkHandle shall be set to 0xffff.
MeasuredDeviceAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the device for which the measurement was executed.
MeasuredDeviceAddress	Short address or extended address	As specified by the DeviceAddrMode parameter	The address of the device for which the measurement was executed.
SrmStatus	Enumeration	SUCCESS, NON_SUPPORTED, REJECTED	The status of the SRM attempt.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

10.28.8.5.3 MLME-SRM-RES.confirm

The MLME-SRM-RES.confirm primitives reports the results of the MLME-SRM-RES.request.

The semantics of this primitive are as follows:

```
MLME-SRM-RES.confirm      (
    SrmHandle,
    Status
)
```

The primitive parameters are defined in Table 10-143.

Table 10-143—MLME-SRM-RES.confirm parameters

Name	Type	Valid range	Description
SrmHandle	Integer	0x00–0xff	An identifier of the corresponding MLME-SRM-RES.request primitive.
Status	Enumeration	SUCCESS, also see 8.2.2	The status of the SRM attempt.

10.28.9 MAC constants and PIB attributes for SRM

10.28.9.1 SRM-specific MAC PIB attributes

Table 10-144 contains the PIB values for SRM. The stored attributes are a snapshot of the last or ongoing measurement, which can be referred to by the upper layer. The usages of these attributes are described in 10.28.

Table 10-144—SRM-specific MAC PIB attributes

Attribute	Type	Range	Description	Default
<i>macEd</i>	Integer	0–254	An estimate of the received signal power within the bandwidth of the channel as defined 11.2.6. Refer to 10.28.2.1. 255 is reserved.	—
<i>macTxFailTime</i>	Integer	0x00–0xff	Percentage of the total transmission attempt time of failed transmissions after all retries with no ACK over the measurement time, linearly scaled with 0xff representing 100%. Refer to 10.28.2.2.	—
<i>macTxDeferred-Time</i>	Integer	0x00–0xff	Percentage of the total backoff period after first CCA over the measurement time, linearly scaled with 0xff representing 100%. Refer to 10.28.2.3.	—
<i>macRetryHistogram</i>	Array	0x00–0xff	Histogram of the number of retries for one transmission during the measurement time. Refer to 10.28.2.4.	—
<i>macChannelUtilization</i>	Integer	0x00–0xff	Total channel used time for Tx and Rx and the occupied time for the other devices. Refer to 10.28.2.5.	—
<i>macRepi</i>	Integer	0x00–0xff	The total channel power (signal, noise, and interference) of a received frame measured on the channel and at the antenna connector used to receive the frame. Refer to 10.28.2.6.	—
<i>macRsni</i>	Integer	0x00–0xff	The signal to noise plus interference ratio of a received frame, which is defined by the ratio of the received signal power to the noise plus interference power as measured on the channel and at the antenna connector used to receive the frame. Refer to 10.28.2.7.	—

Table 10-144—SRM-specific MAC PIB attributes (continued)

Attribute	Type	Range	Description	Default
<i>macRssi</i>	Integer	0–254	The RF power level at the input of the transceiver. Refer to 10.28.2.8.	—
<i>macNoiseHistogram</i>	Array of Integers	—	Power histogram measurement of non-IEEE 802.15 noise power. Refer to 10.28.2.9.	—
<i>macFrameErrorCount</i>	Integer	$0\text{--}2^{8\times macCounterOctets-1}$	The number of received frames that were discarded due to any error except for FCS error (complementary to <i>macFcsErrorCount</i> in 10.27.3.1).	—
<i>macCounterOctets</i>	Integer	As defined in 10.27.3.1	See 10.27.3.1 (existing metric).	—
<i>macRetryCount</i>	Integer	As defined in 10.27.3.1	See 10.27.3.1 (existing metric).	—
<i>macMultipleRetryCount</i>	Integer	As defined in 10.27.3.1	See 10.27.3.1 (existing metric).	—
<i>macTxFailCount</i>	Integer	As defined in 10.27.3.1	See 10.27.3.1 (existing metric).	—
<i>macTxSuccessCount</i>	Integer	As defined in 10.27.3.1	See 10.27.3.1 (existing metric).	—
<i>macFcsErrorCount</i>	Integer	As defined in 10.27.3.1	See 10.27.3.1 (existing metric).	—
<i>macSecurityFailure</i>	Integer	As defined in 10.27.3.1	See 10.27.3.1 (existing metric).	—
<i>macDuplicateFrameCount</i>	Integer	As defined in 10.27.3.1	See 10.27.3.1 (existing metric).	—
<i>macRxSuccessCount</i>	Integer	As defined in 10.27.3.1	See 10.27.3.1 (existing metric).	—
<i>macNackCount</i>	Integer	As defined in 10.27.3.1	See 10.27.3.1 (existing metric).	—
<i>macDeferredTxCount</i>	Integer	$0\text{--}2^{8\times macCounterOctets-1}$	The number of times the CSMA-CA algorithm was required to backoff as described in 6.3.2.	—
<i>macAverageBufferUtilization</i>	Integer	0–100	The average percentage of the used buffer space in Tx queue.	—
<i>macMaximumBufferUtilization</i>	Integer	0–100	The maximum percentage of the used buffer space in Tx queue.	—
<i>macTxFragmentCount</i>	Integer	$0\text{--}2^{8\times macCounterOctets-1}$	The number of transmitted fragments.	
<i>macRxFragmentCount</i>	Integer	$0\text{--}2^{8\times macCounterOctets-1}$	The number of fragments received.	
<i>macTxMulticastCount</i>	Integer	$0\text{--}2^{8\times macCounterOctets-1}$	The number of transmitted multicast frames.	
<i>macRxMulticastCount</i>	Integer	$0\text{--}2^{8\times macCounterOctets-1}$	The number of multicast frames received.	

Table 10-144—SRM-specific MAC PIB attributes (continued)

Attribute	Type	Range	Description	Default
<i>macAverageAccessDelay</i>	Integer	$0\text{--}2^{8\times macCounterOctets}-1$	The average medium access delay for transmitted frames measured from the time the MPDU is ready for transmission until the actual frame transmission start time. Refer to 10.28.2.10.	—
<i>macSrmChannel-Number</i>	Channel information structure as defined in 11.1.3.1	Any valid channel	Channel for measurement. When used in the frames only the channel number part of the channel information structure is used.	—
<i>macSrmRxAddrMode</i>	Enumeration	SHORT, EXTENDED	Address mode of the received frame that is used for measurement.	—
<i>macSrmRxDeviceAddress</i>	As specified by the <i>macRxAddrMode</i> parameter		Source address of the received frame that is used for measurement.	—
<i>macSrmStartTime</i>	Integer	0x00–0xff	The remaining time to start the next measurement that can be referred to by the upper layer. If this value is zero, the requested measurement has been started or finished.	—
<i>macSrmDuration</i>	Integer	0x0000–0xffff	The remaining duration of the next or ongoing measurement that can be referred to by the upper layer. If this value is zero, the requested measurement has been finished.	—
<i>macSRMmeasurementMode</i>	Integer	0x00–0x02	In the case of TSCH, the following modes can be applied; otherwise the full measurement (0x00) is applied. Full measurement (0x00): the measurement is conducted wherever the channel is hopped. Channel-specific measurement (0x01): the measurement is conducted only on the specified channel. Link-specific measurement (0x02): the measurement is conducted only on the specified Link.	—

10.29 Ranging

10.29.1 Ranging measurements

10.29.1.1 Overview

Support for ranging is optional. A device that supports ranging is called an RDEV. An RDEV shall support the ranging counter described in 10.29.1.3 and the FoM described in 10.29.1.7. An RDEV may support optional crystal characterization described in 10.29.1.6 and the optional dynamic preamble code (DPS) and channel selection (DCS) managed as per 10.29.4 and described in “Application of IEEE Std 802.15.4” [B4].

RDEVs produce ranging results, used by higher layers to compute the ranges between devices. These ranging results may include transmit and receive ranging counter values, ranging FoM, angle of arrival (AOA) information, ranging tracking interval, and ranging tracking offset values.

This standard includes optional features to support relative positioning and localization. Accurate location may be achieved by an RDEV using one of the ultra wideband (UWB) PHYs defined in this standard that provide the capability to accurately determine packet reception and transmission times. With accurate message timestamping, techniques such as two-way ranging (TWR) time of flight (TOF) can give very accurate estimates of relative separation distance between two devices. Similarly, an accurate location estimate for a mobile device can be determined, for example, when its distance from a number of fixed devices (of known location) is ascertained.

The UWB PHYs specified in Clause 16 and Clause 19 optionally include facilities to enhance ranging, and these ERDEVs are referred to as the HRP-ERDEV and the low rate pulse repetition frequency UWB PHY based enhanced ranging capable device (LRP-ERDEV), respectively.

The HRP-ERDEV incorporates an STS, see 16.2.9, generated by an AES-128 based deterministic random bit generator (DRBG). Only valid transmitters and receivers know the correct seed to generate the sequence for transmission and for reception to cross correlate and accumulate to produce a channel impulse response estimate from which to accurately determine the receive time.

The LRP-ERDEV supports challenge-response authenticated ranging with distance commitment on secret data payload. These ranging schemes are described in 10.33.

The fundamental measurements for ranging are achieved using a transmitted frame and a response frame. For example, a ranging exchange may consist of a Data frame and its acknowledgment. As another example, the response could be a Data frame. A frame used for a ranging measurement is referred to as an RFRAME. Generally, an RFRAME is indicated by the Ranging field being set in the PHR, however as described in 16.2, the HRP-ERDEV has a packet configuration where the PPDU has no PHR (or data) but consists solely of the SHR and STS. This is an SP3 packet. SP3 packets are treated as RFRAMEs.

Ranging capabilities are enabled in an RDEV with the MCPS-DATA.request primitive and with the MLME-RX-ENABLE.request primitive. Whenever ranging is enabled in an RDEV, the RDEV delivers accurate transmit and receive time reports to the next higher layer as a result of events at the device antenna. The times that are reported are measured relative to the RMARKER. For all PHYs the RMARKER is defined to be the time when the beginning of the first symbol following the SFD of the RFRAME is at the local antenna. For UWB PHYs this shall be the peak pulse location associated with the first chip following the SFD. An HRP-ERDEV can use the STS to determine time of arrival and then derive the RMARKER time.

The relative positioning and locating methods supported by this standard are: single-sided two-way ranging (SS-TWR), double-sided two-way ranging (DS-TWR), and one-way ranging (OWR) for the time difference of arrival (TDOA) localization method.

In a typical implementation, the transmit and receive time reports will be captured by the transmitter and receiver, and then adjusted to account for the time difference between the internally captured time and the time the RMARKER actually launches or arrives at the antenna. These offsets are separately defined for transmitter and receiver as the configurable PIB attributes *phyTxRmarkerOffset* and *phyRxRmarkerOffset*.

The TxRangingCounter and RxRangingCounter values within the RangingReportDescriptor (defined in Table 8-28) parameter of the MCPS-DATA.confirm and MCPS-DATA.indication primitives report RMARKER transmit and receive times as specified in 8.3.

The next higher layer can estimate the relative clock offset between the remote transmitter and the local reference clock at the receiver based on the reported STS RMARKER (SRMARKER) receive ranging counter values for one or more STS segments. This allows estimation of individual clock offsets per subsystem in case different subsystems are used to transmit or receive different STS segments, e.g., in ranging nodes featuring antenna diversity. For example, to determine the relative clock offset via the first STS segment, the following calculation can be used:

$$\frac{f_{\text{ref.remote}}}{f_{\text{ref.local}}} = \frac{L_{\text{segment.ideal}}}{\text{RxS1RangingCounter} - \text{RxS0RangingCounter}}$$

10.29.1.2 Ranging and localization methods

10.29.1.2.1 Preface

The ranging and localization methods supported by RDEVs and ERDEVs are based on the timestamping capability. The three main time-based techniques for performing ranging and localization are as follows:

- SS-TWR, described in 10.29.1.2.2.
- DS-TWR, described in 10.29.1.2.3.
- OWR/TDOA, described in 10.29.1.2.5.

The following nomenclature is used:

- Initiator: The RDEV that starts a ranging exchange by sending the first RFRAME in the exchange.
- Responder: The RDEV that responds to the initiation RFRAME.

10.29.1.2.2 Single-sided two-way ranging (SS-TWR)

SS-TWR involves a measurement of the round-trip delay of a single message from one device to another and a response sent back to the original device. The operation of SS-TWR is as shown in Figure 10-197, where device A initiates the exchange and device B responds to complete the exchange and T_{prop} is the propagation time of the RMARKER between the devices.

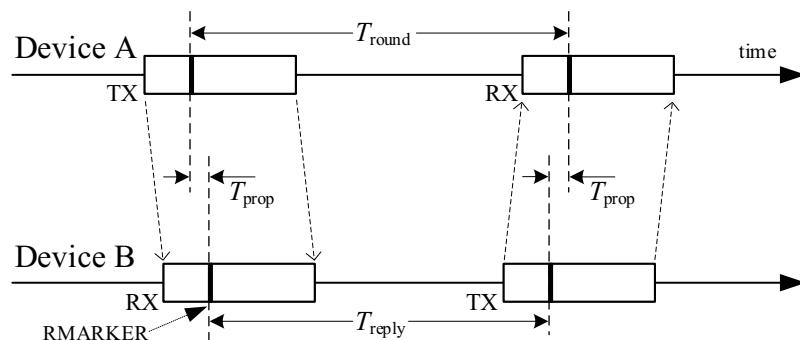


Figure 10-197—SS-TWR

Each device precisely measures the transmission and reception times of the message frames, and so can calculate times T_{round} and T_{reply} by simple subtraction. Hence, the resultant TOF may be estimated as \hat{T}_{prop} by the equation:

$$\hat{T}_{\text{prop}} = \frac{1}{2} \times (T_{\text{round}} - T_{\text{reply}})$$

The times T_{round} and T_{reply} are measured independently by device A and B using their local clocks, which both have some clock frequency offset error e_A and e_B , respectively, from their nominal frequency. Therefore, the resulting TOF estimate has a considerable error that increases as the reply times get larger, as explained in “Application of IEEE Std 802.15.4” [B4]. However if the receiver of device A has the capability to measure the relative clock offset between itself and the remote device B transmitter, C_{offs} , then this may be used to adjust the reported T_{reply} value to improve the accuracy of the TOF estimate using the equation:

$$\hat{T}_{\text{prop}} = \frac{1}{2} \times (T_{\text{round}} - T_{\text{reply}} \times (1 - C_{\text{offs}}))$$

When the receiver has the capability to measure the relative clock frequency offset this is reported via the RangingTrackingInterval and RangingOffset parameters of the MCPS-DATA.confirm or MCPS-DATA.indication primitives.

When employing SS-TWR, for the TOF to be calculated at device A, device A needs the reply time T_{reply} employed by device B. When T_{reply} is determined by device B after its transmission, an additional message is necessary to bring this value to device A, as shown in Figure 10-203 and described in 10.29.6.3. When T_{reply} can be accurately predicted by device B before its transmission, the value can be embedded in the reply message itself, as shown in Figure 10-204 and described in 10.29.6.4. Alternatively, if device B has the ability to always reply with sufficiently accurate constant or pre-known reply time, it obviates the need for any transfer of T_{reply} as part of the ranging exchange, as described in 10.29.6.5.

10.29.1.2.3 Double-sided two-way ranging (DS-TWR)

DS-TWR is an extension of SS-TWR in which two round-trip time measurements are used and combined to give the TOF result with a reduced error in the presence of uncorrected clock frequency offset even for quite long response delays. The operation of DS-TWR is shown in Figure 10-198, where device A initiates the first round-trip time measurement to which device B responds, after which device B initiates the second round-trip time measurement to which device A responds, completing the full DS-TWR exchange and T_{prop} is the propagation time of the RMARKER between the devices.

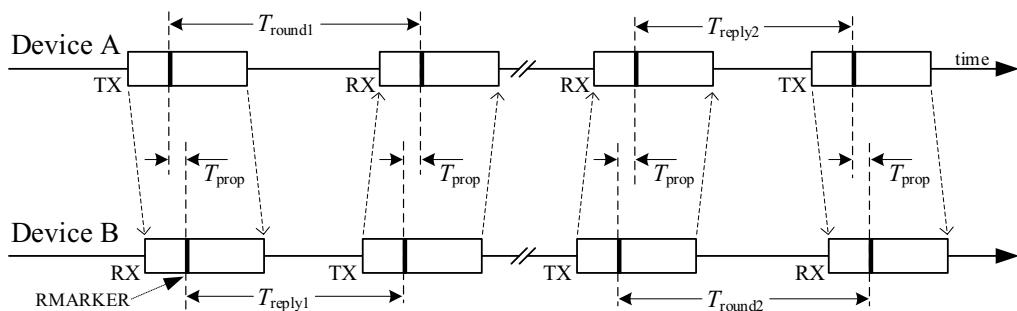


Figure 10-198—DS-TWR

Each device precisely measures the transmission and reception times of the messages, and the resultant TOF may be estimated as \hat{T}_{prop} by the equation:

$$\hat{T}_{\text{prop}} = \frac{(T_{\text{round1}} \times T_{\text{round2}} - T_{\text{reply1}} \times T_{\text{reply2}})}{(T_{\text{round1}} + T_{\text{round2}} + T_{\text{reply1}} + T_{\text{reply2}})}$$

NOTE—This formula does not require symmetric reply times. The typical clock induced error is in the low picosecond range even with 20 ppm crystals and asymmetric response times. The derivation of this formula and the error calculation can be found in IEEE Std 802.15.8™-2017, Annex D, subclause D2 [B14].

10.29.1.2.4 DS-TWR with three messages

The four messages of DS-TWR, shown in Figure 10-198, can be reduced to three messages by using the reply of the first round-trip time measurement as the initiator of the second round-trip time measurement. This is shown in Figure 10-199.

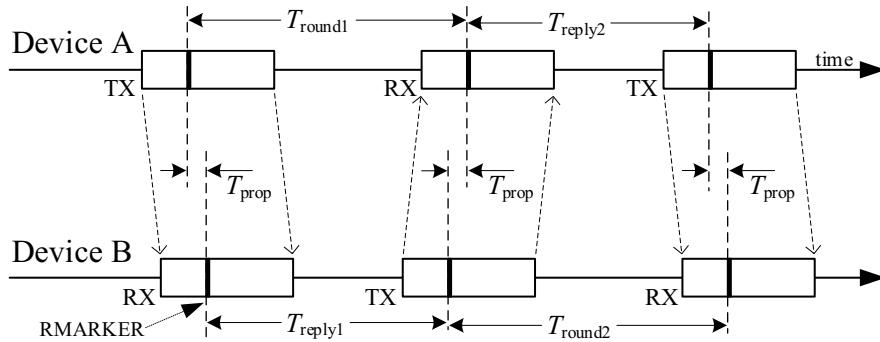


Figure 10-199—DS-TWR with three messages

10.29.1.2.5 Time difference of arrival (TDOA)

TDOA is a technique to locate a mobile device, (e.g., RFID device), based on the relative arrival times of a single message or multiple messages. OWR is used for TDOA. There are two cases of TDOA. In one case a message is periodically broadcast by the mobile device to multiple fixed nodes that are synchronized in some way so that the arrival times can be compared. Typically, the message sent by the mobile device is referred to as a blink. In the other case, multiple synchronized nodes broadcast messages sequentially with known transmission time offsets with respect to each other. For any pair of fixed synchronized nodes, the difference in arrival time of the blink in the first case, or the broadcast messages at the mobile device in the second case, places the mobile device on a hyperbolic surface. Combining the results from multiple such pairs will yield an intersection point between the sets of hyperbolic surfaces yielding the location of the mobile device. Note that in the second case, the transmission offset is taken into account when calculating the difference in arrival time of messages from synchronized nodes.

RFID devices typically use the shortest blink message possible, (e.g., a multipurpose frame) to reduce power consumption. A multipurpose frame can be as short as 12 octets; consisting of a Short Frame Control field, the Sequence Number field, no Destination Address field, an extended source address and an FCS.

Synchronization of fixed nodes can be achieved by a wired distribution of the clock signals. However wireless synchronization schemes are also practical. These may use UWB messages sent between the fixed nodes (and a known/pre-measured TOF) to calculate the relative clock frequency offset and drift between the fixed nodes and use this information to correct the arrival times of the blink messages into a common timebase for the TDOA data to be meaningful.

10.29.1.3 Ranging counter

The ranging counter supported by an RDEV is a set of behavioral properties and capabilities of the RDEV that produce ranging counter values. A ranging counter value is an unsigned integer of, at minimum, 32-bit length. The unit of this counter is specified in 10.29.1.4.

10.29.1.4 Ranging counter time unit

The time unit of the ranging counter as used in MCPS-DATA primitives and ranging time related IEs differs depending on the PHY.

- For the HRP UWB PHY, the time unit is 2^{-7} of the 499.2 MHz chipping period, which is approximately 15.65 ps.
- For the LRP UWB PHY, the time unit is 2^{-20} of the basic chipping rate of 1 MHz, which is approximately 0.9537 ps.
- For the TVWS PHY, the time unit is 10 ps.

The next higher layer is responsible for the TOF calculations and interpreting the time unit of the ranging counter correctly depending on the current PHY.

10.29.1.5 Ranging scheduling time unit (RSTU)

The RSTU applies in the MAC for specifying ranging slot durations and various time intervals for scheduling of ranging activities. The RSTU value depends on the current PHY as specified in Table 10-145.

Table 10-145—PHY dependent RSTU values

PHY	RSTU
HRP UWB PHY	416 chips = $416 \div (499.2 \times 10^6)$ = approximately 833.33 ns
LRP UWB PHY	1 chip at 1 MHz basic chipping rate = 1 μ s

The ERDEV MAC shall maintain a 24-bit RSTU time counter relative to which slot timings and associated packet transmissions and receive enables are referenced.

10.29.1.6 Crystal characterization

10.29.1.6.1 Crystal characterization overview

An RDEV that implements optional crystal characterization shall produce a tracking offset value and a tracking interval value for every ranging report. The tracking offset and the tracking interval are computed from measurements taken during an interval that includes the interval bounded by the ranging counter start value and the ranging counter stop value.

NOTE—Crystal characterization is relevant only if it is characterizing the crystal that affects the ranging counter.

10.29.1.6.2 Ranging tracking offset

The ranging tracking offset provides information on the difference between the transmitter and receiver reference oscillator frequencies. The value is a signed integer, which shall be positive when the oscillator at the transmitter operates at a higher frequency than the oscillator at the receiver, and negative when the

oscillator at the transmitter operates at a lower frequency than the oscillator at the receiver. The value represents the difference in frequency between the receiver's oscillator and the transmitter's oscillator after the tracking offset integer is divided by the ranging tracking interval integer of 10.29.1.6.3. The precision shall be at least 19 bits.

10.29.1.6.3 Ranging tracking interval

The ranging tracking interval is an unsigned integer value that represents the duration in a message exchange over which the tracking offset was measured. The size of the ranging tracking interval should be chosen to allow reporting (in conjunction with the ranging tracking offset value defined in 10.29.1.6.2) of crystal offset values down to 100 parts per billion, or better. Greater precision is encouraged, as described in “Application of IEEE Std 802.15.4” [B4].

10.29.1.7 Ranging FoM

An RDEV shall produce a Ranging FoM for every ranging counter value that is produced. The Ranging FoM shall be formatted as shown in Figure 10-200.

Bits: 0–2	3–4	5–6	7
Confidence Level	Confidence Interval	Confidence Interval Scaling Factor	Extension

Figure 10-200—Ranging FoM

The Confidence Level field conveys the probability that the RMARKER arrived during the Confidence Interval, as specified in Table 10-146.

The Confidence Interval field specifies the confidence interval as defined in Table 10-147. The duration of the Confidence Interval in Table 10-147 is the duration of the entire interval, not a plus or minus number.

The Confidence Interval Scaling Factor field is defined in Table 10-148.

The overall confidence interval is obtained according to the formula:

$$\text{Overall confidence interval} = \text{Confidence Interval} \times \text{Confidence Interval Scaling Factor.}$$

When the Extension field is zero, the fields have the meanings given in Table 10-146, Table 10-147, and Table 10-148.

Table 10-146—Confidence Level field

Confidence Level field value	Confidence level
0	No FoM
1	20%
2	55%
3	75%
4	85%

Table 10-146—Confidence Level field (continued)

Confidence Level field value	Confidence level
5	92%
6	97%
7	99%

Table 10-147—Confidence Interval field

Confidence Interval field value	Confidence interval
0	100 ps
1	300 ps
2	1 ns
3	3 ns

Table 10-148—Confidence Interval Scaling Factor field

Confidence Interval Scaling Factor field value	Confidence interval scaling factor
0	0.5
1	1.0
2	2.0
3	4.0

The FoM characterizes the accuracy of the PHY estimate of the arrival time of the RMARKER at the antenna. The FoM shall characterize the accuracy of the timer counter value in the same report primitive.

When the Extension field is set to one, the Ranging FoM shall be formatted as shown in Figure 10-201.

Bits: 0–6	7
Extension Value	Extension = 1

Figure 10-201—Ranging FoM format when the Extension field is one

The FoM value having its Extension field set to one and Extension Value field set to zero is specifically used to signal to the next higher layer that the RxRangingCounter value is not correct and the higher layer should use the sounding primitives, for example MLME-SOUNDING.request, see 10.29.9.2, to retrieve the channel sounding information and use it to determine the ranging counter value to ascribe to the received packet. All other Extension Value field values are reserved.

10.29.2 Set-up activities before a ranging exchange

The mandatory part of ranging is limited to the generation of transmit and receive ranging counter time reports during the period that ranging is enabled in an RDEV. It is possible that an RDEV will consume more power when ranging is enabled; therefore, a natural default for an application would be to have ranging disabled. The higher layer is responsible for enabling ranging in both RDEVs involved in a TWR exchange. Furthermore, if the optional DPS capability is to be used, it is assumed there has been some sort of coordination of the preamble and channel selection prior to the TWR exchange. How this coordination is accomplished is up to the implementer. The Ranging Channel and Preamble Code Selection IE (RCPCS IE), as specified in 10.29.8.5, can be included in a frame exchange prior to the ranging exchange, or out-of-band signaling, as well as custom messages, may be used for this coordination.

10.29.3 Finish-up activities after a ranging exchange

At the end of a two-way exchange, each device is in possession of TX and RX ranging counter values giving the round-trip time measurement or reply time as appropriate. To compute the TOF, both of these values are needed at the node where the computations are performed. How this movement of these values is accomplished is up to the implementer. Out-of-band signaling as well as custom messages or the Ranging Measurement Information IE (RMI IE), as specified in 10.29.8.4, can be used for this purpose as described in 10.29.6.3.

10.29.4 Managing DPS and dynamic channel selection (DCS)

10.29.4.1 Managing DPS

Figure 10-202 shows a suggested message sequence for TWR. The messages represented in the two top dotted boxes are simply suggestions showing how the communications capability of the RDEV can be used to accomplish the ranging setup activities. The messages in the bottom dotted box are suggestions showing how the communications capability of the RDEV can be used to accomplish the ranging finish-up activities.

The top dotted box in Figure 10-202 illustrates the use of a data exchange to effect the coordination of the preamble codes and channel to be used for a TWR exchange. The coordination is needed only when using the optional DPS capability of the PHY. As illustrated in Figure 10-202, for the ERDEV, the choice of preamble code and channel number can be exchanged using the RCPCS IE (described in 10.29.8.5). If optional DPS is not used, the communication sequence in the top box can be thought of as arranging for the recipient RDEV to become aware that a ranging exchange is desired and that the recipient next higher layer should enable ranging in the recipient PHY. The second from the top dotted box in Figure 10-202 illustrates the use of the MLME-DPS.request, as described in 10.29.9.1.2, and the MLME-DPS.confirm, as described in 10.29.9.1.3. Use of these primitives is unique to the optional DPS mode of ranging.

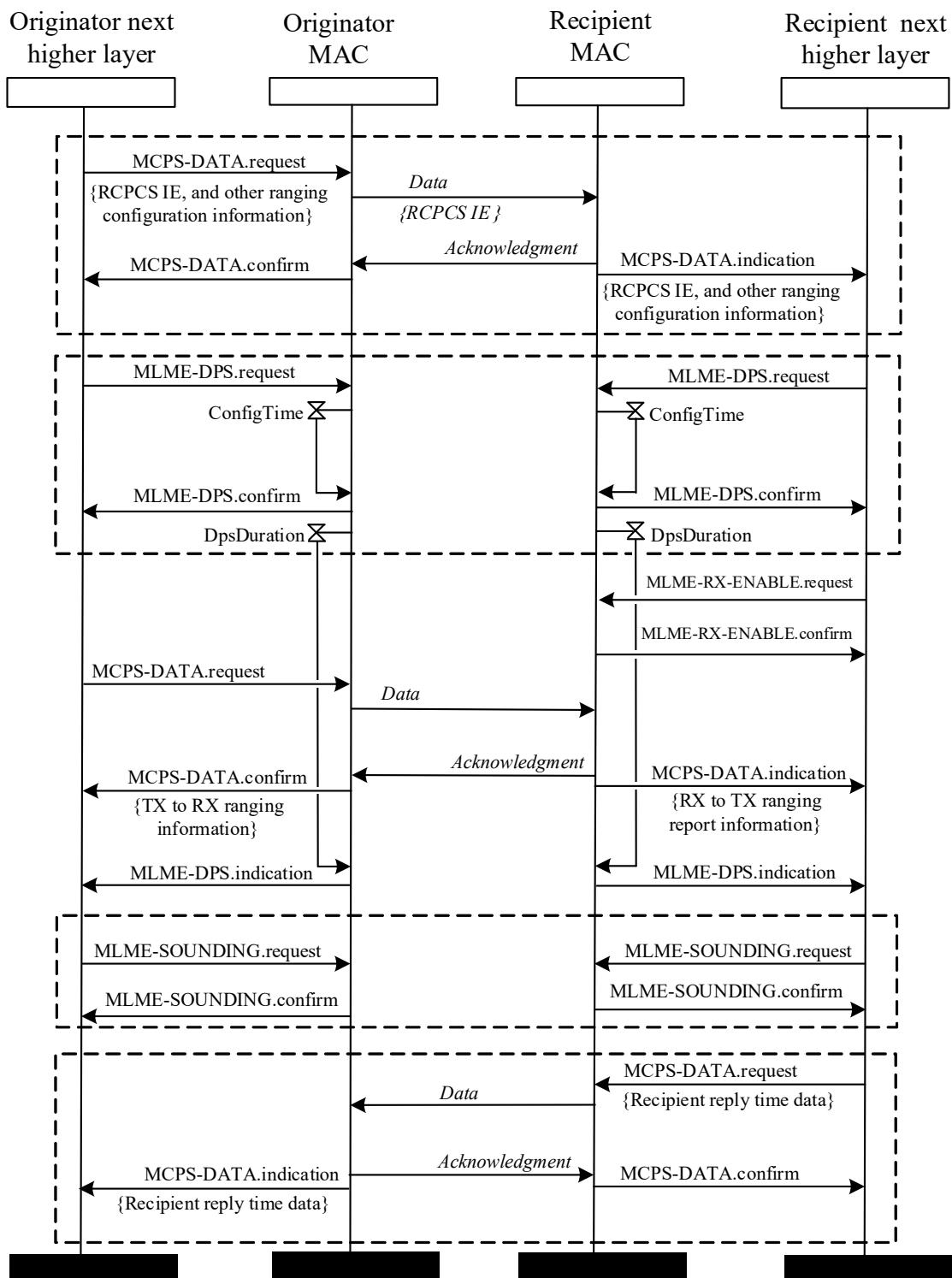


Figure 10-202—A message sequence for ranging

The next higher layer of the ERDEV can optionally specify a future time at which to apply the preamble code and/or channel number using the ConfigTime parameter of the MLME-DPS.request. The time at which to make the DPS change can be exchanged via the CCI field of the RCPSC IE. It is the responsibility of the next higher layer to make channel selection that reflects the regional regulation. If the selected channel is not supported by the device, the DPS will fail, and the MLME-DPS.confirm primitive shall report a Status parameter value of NOT_SUPPORTED.

Upon the assertion of the MLME-DPS.confirm primitives, as illustrated in Figure 10-202, both of the devices have switched to use the alternative preamble symbols and/or channel number as selected by the MLME-DPS.request. This is desirable behavior intended to help hide the transmissions from other nodes in the network and protect the devices from transmissions by other nodes in the network. A side effect of this mode is that neither device can communicate with the rest of the network. To avoid the devices from losing connectivity as a result of this behavior, the MAC sublayers on both sides of the link shall initiate timers after issuing the MLME-DPS.confirm with Status of SUCCESS. If the timer duration is exceeded before the MAC sublayer issues the MCPS-DATA.confirm (for the originator) or the MCPS-DATA.indication primitive (for the recipient), then the MAC sublayer shall initiate an MLME-DPS.indication to the next higher layer as described in 10.29.9.1.4. Not shown in Figure 10-202, one responsibility of the application, if the optional DPS capability is used, is to initiate the MLME-DPS.request primitive on both sides of the ranging link at the completion of the ranging exchange to return the PHYs to using *phyCurrentCode* and *phyCurrentChannelInfo* from the PIB.

10.29.5 The basic ranging exchange

This subclause describes the basic ranging exchange. Enhanced ranging procedures that employ IEs for their control and for ranging information exchange are described in 10.29.6 and 10.32. These subclauses include message sequence charts to illustrate the procedures. The use and support of any of these ranging procedures and associated IEs is optional.

The essential core of the ranging exchange is shown in Figure 10-202 starting just below the MLME-DPS exchange. The application is responsible for initiating the MLME-RX-ENABLE.request primitive, as described in 8.2.7.3, with RangingControl equal to RANGING_ON. Once the RDEV has received the MLME-RX-ENABLE.request primitive with RangingControl equal to RANGING_ON, all future RFRAMES received by the RDEV shall generate TX and RX ranging counter reports until ranging is disabled.

At the initiator, the application is responsible for initiating an MCPS-DATA.request primitive with Ranging and RangingPhr values (in the DataRequestRangingDescriptor parameter) both set to TRUE. Upon receipt of an MCPS-DATA.request primitive with Ranging equal to TRUE, an RDEV shall generate ranging reports for all RFRAMES after the transmit frame is transmitted. The ranging reports will continue until ranging is disabled. The TX-to-RX turnaround enabling the originator to receive the Ack frame is necessary and is not shown in Figure 10-202. This turnaround is the normal turnaround that is done for any exchange expecting an acknowledgment. The turnaround happens without any action required by the originator next higher layer. Ranging reports are generated and passed to the next higher layer independent of the state of the AR field in the MAC header of received RFRAMES.

As shown in Figure 10-202, the first ranging report to the originator next higher layer shall be provided by the MCPS-DATA.confirm primitive. The first ranging report to the recipient next higher layer is via parameters of the MCPS-DATA.indication primitive. All subsequent ranging reports on either side of the link are via parameters of MCPS-DATA.indication and MCPS-DATA.confirm primitives. The potential additional MCPS-DATA.indication primitives that may be due to unexpected stray RFRAMES are not shown in Figure 10-202 for simplicity. The timestamp reports due to any strays shall continue until ranging is disabled. The generation of ranging reports for a stream of stray RFRAMES is the behavior that enables the RDEV to be used as an infrastructure RDEV in OWR applications. OWR is described in “Application of IEEE Std 802.15.4” [B4].

For non-TVWS RDEVs, the timestamp is defined in 10.29.1.1. Use of nonzero TX and RX ranging counter reports is limited to RDEVs. Only devices that have *phyRanging* set to TRUE shall return a ranging report to a next higher layer.

For TVWS RDEVs, the Timestamp IE, 10.7.3.9, and the Timestamp Difference IE, 10.7.3.10, are provided for exchanging timing information between TVWS RDEVs to support the ranging feature.

For information on the use of the MLME-SOUNDING primitives see section 7.1.1.4.5 of “Application of IEEE Std 802.15.4” [B4].

10.29.6 Ranging procedures

10.29.6.1 General ranging procedures

The layers above the MAC are responsible for the decision to participate in a TWR exchange between a pair of devices and for the final calculation of the resulting range. Ranging procedures appropriate to the ranging methods described in 10.29.1.2 are defined in 10.29.6, 10.32, and 10.33. The use and support of any of these ranging procedures and associated IEs is optional.

Irrespective of whether the ranging reports are coming from an RDEV or an ERDEV, the same procedures apply, (i.e., any reference to RDEVs also applies to ERDEVs). However, an ERDEV provides additional primitives, based on which the higher layer can modify the action it takes (e.g., replying in a ranging exchange, or considering the ranging result as good) depending on its validation of the timestamp result. For example, in the case of the HRP-ERDEV this may be done using the RangingStsFom parameter(s) of the MCPS-DATA.indication primitive.

10.29.6.2 Control of ranging and the transfer of results

Information elements can be employed to control TWR and the transfer of ranging data between the RDEVs participating in the ranging exchange. With reference to the ranging methods defined in 10.29.1.2.2 and 10.29.1.2.3, to complete the calculation of the TOF between two RDEVs participating in a ranging exchange, depending on the use case it is necessary to combine measurements made by both devices. That is, one device will need to transfer its ranging measurements to the other. Information elements are specified to provide a mechanism to control TWR and support the transfer of ranging information between the devices participating in the ranging exchange. It is recommended to employ the secure private data communication capability of this standard.

10.29.6.3 Ranging procedure for SS-TWR with deferred reply time result

For an SS-TWR with a deferred reply time result, the ranging exchange is initiated by the next higher layer invoking the MCPS-DATA.request primitive to send a ranging frame including the Ranging Request Measurement and Control IE (RRMC IE), described in 10.29.8.3, requesting the ranging reply time information, and with the Ranging Control Information field set according to Table 10-151.

The replying ranging frame completes the round-trip time measurement and the MCPS-DATA.confirm primitive gives the initiating side a ranging report that defines the round-trip time. At the responding side, the MCPS-DATA.indication primitive supplies the responding side ranging report that defines the reply time for the round-trip time measurement. This reply time is communicated to the initiating side in the RMI IE (described in 10.29.8.4), carried by a subsequent message.

Figure 10-203 shows the message sequence chart for this exchange, where RRMC IE (0) indicates an RRMC IE with the Ranging Control Information field value of zero. When the initiator next higher layer

receives the RMI IE it has sufficient information to calculate the TOF between the two devices using one of the formulas given in 10.29.1.2.2.

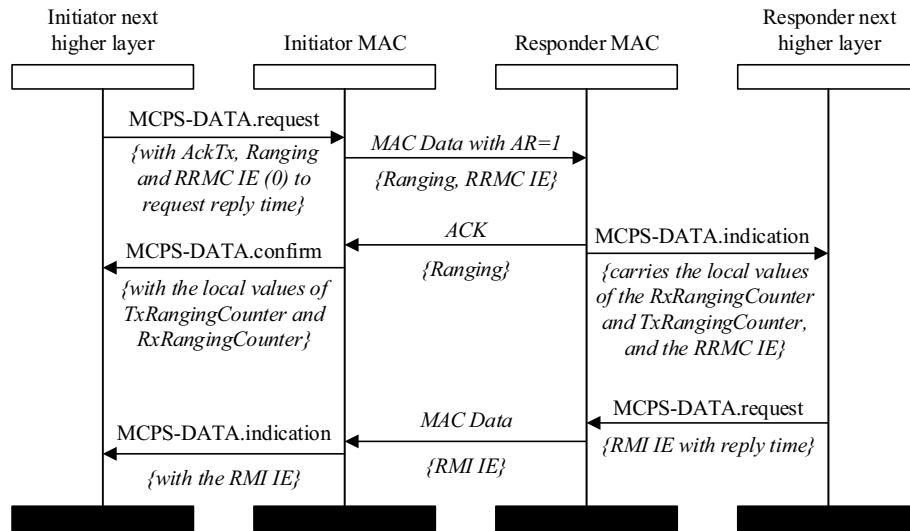


Figure 10-203—Message sequence chart for SS-TWR with deferred reply time result

10.29.6.4 Ranging procedure for SS-TWR with embedded reply time result

For an SS-TWR with an embedded reply time result, the ranging exchange is initiated by a ranging frame including the RRMC IE (described in 10.29.8.3) requesting the ranging reply time information, and with the Ranging Control Information field set according to Table 10-151. The responding device completes the round-trip measurement by sending a reply frame with an embedded Ranging Reply Time Instantaneous IE (RRTI IE) as specified in 10.29.8.1. When a device is capable of generating an RRTI IE, it can minimize the number of messages needed for a ranging measurement and thus save power, see Figure 10-197 and its associated description in 10.29.1.2.2 for details. However, it takes time to calculate the arrival time of the received ranging message and prepare the RRTI IE value. While in some cases this time may be known a priori by an out-of-band means, the Ranging Reply Time Negotiation IE (RRTN IE) as specified in 10.29.8.6 provides a mechanism for such a device to indicate its preferred reply time, that is how long it needs to prepare the frame with the RRTI IE. When this time is known, the ranging initiating device can expect the response message after the specified time and can save energy by delaying turning on the receiver until then. This is applicable in both SS-TWR and DS-TWR ranging exchanges.

Figure 10-204 shows the message sequence chart for this exchange, where RRMC IE (0) indicates an RRMC IE with the Ranging Control Information field value of zero. The communication of the RRTN IE, shown in the dashed box, may happen at any convenient time before the ranging exchange is initiated, or the preferred reply time information may be pre-known or exchanged out-of-band. Upon receipt of the MCPS-DATA.indication primitive conveying the responder's RRTI IE, the initiator next higher layer has sufficient information to calculate the TOF between the two devices according to one of the formulas given in 10.29.1.2.2.

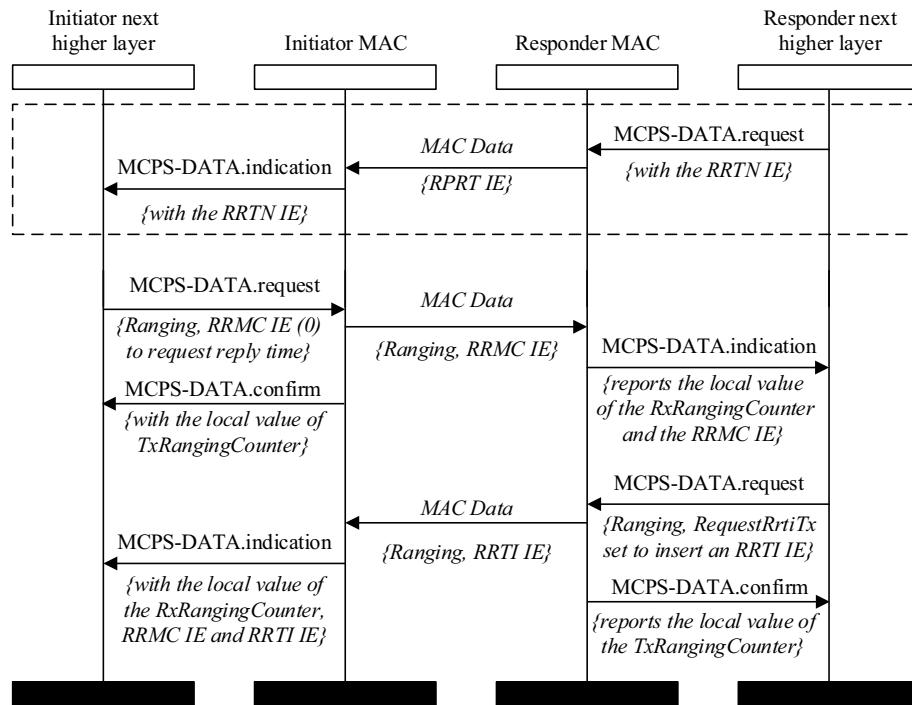


Figure 10-204—Message sequence chart for SS-TWR with embedded reply time

10.29.6.5 Ranging procedure for SS-TWR with fixed reply time

Where a responding device has precise control of the transmit time of its response message with respect to the arrival time of the ranging initiation message, then the reply time, T_{reply} in Figure 10-197, may be a fixed known quantity, agreed between the parties participating in the ranging exchange. In this case it is not required to embed T_{reply} into the response message or to send it separately in an additional message. The accuracy of the resultant range will depend on how fine a control the responding device has on the transmit time of its response message, where every 1 ns error in TOF translates to approximately 30 cm range error.

The HRP-ERDEV PPDU format SP3 might be employed in the case of fixed reply time. Figure 10-205 shows an example message sequence chart for such a ranging exchange.

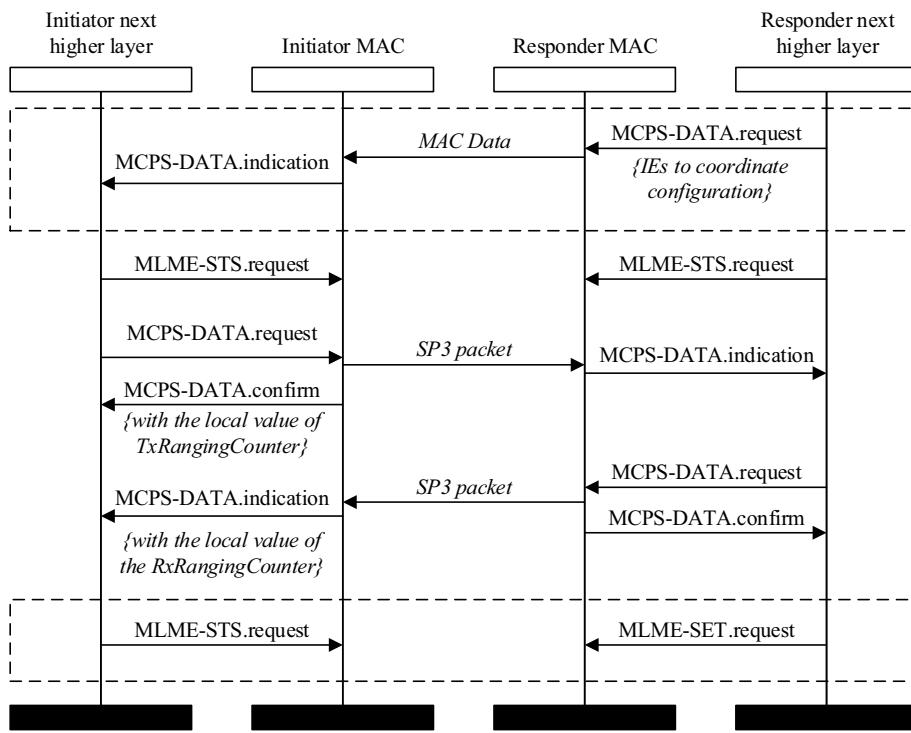


Figure 10-205—Message sequence chart for SS-TWR using SP3 packets

The initial message in the dashed box represents the communication between devices to coordinate and agree on the use of SP3 packets and on all other necessary parameters to allow the communication to proceed. While only a single message is shown in the figure, there may be a series of messages in each direction to agree on all the parameters. For example, the RRTN IE (described in 10.29.8.6) can be used to agree on the fixed reply time.

The next higher layer is responsible for properly configuring the operation at each end using the MLME-STS.request primitive to configure the SP3 packet format at both ends, and for setting the PIB attributes *phyHrpUwbStsSeed*, *phyHrpUwbStsVCounter*, and *phyHrpUwbStsVUpper96* to the correct values. Once the higher layer has selected the SP3 packet configuration, subsequent MCPS-DATA primitives relate to SP3 packets, until the higher layer uses the MLME-STS.request primitive to change the packet configuration.

The MCPS-DATA.request primitive is used to initiate the ranging exchange, even though in this mode the PPDU does not convey MAC data. Not shown, but assumed, is the invoking of the MLME-RX-ENABLE.request primitive to turn on the receiver at the appropriate time to receive the PPDU. Since the PHY is configured for SP3 packets, the PHY indicates reception of the PPDU to the MAC layer at the end of the STS and the MAC, similarly aware of the SP3 configuration, delivers the RxRangingCounter value in the RangingReportDescriptor parameter of the MCPS-DATA.indication primitive. Also, assuming the RangingStsFom in the RangingReportDescriptor is acceptable, the higher layer may initiate the response by invoking an MCPS-DATA.request primitive specifying a RangingTxTime in line with the agreed fixed reply time.

When the SP3 packet response is received at the initiating device, and again assuming that the RangingStsFom in the RangingReportDescriptor parameter of that MCPS-DATA.indication primitive is

acceptable, the initiating end has sufficient information, given the known fixed reply time, to calculate the TOF between the two devices according to one of the formulas given in 10.29.1.2.2.

The ranging exchanges are repeated as many times as the higher layers have mutually agreed. To resume PHY and MAC data interactions, the next higher layer uses the MLME-STS.request primitive to restore the STS packet configuration to a value that allows such data interactions. This is shown in the final dashed box in Figure 10-205.

The LRP-ERDEV also supports challenge-response ranging with fixed reply time, to remove the need for a data message to convey the reply time. The procedures for this are defined in 10.33.5.

10.29.6.6 Ranging procedure for DS-TWR with deferred reply time information

DS-TWR essentially involves completing SS-TWR exchanges initiated at either end and combining the results. The DS-TWR exchange is initiated by the next higher layer sending a ranging Data frame carrying an RRMC IE (described in 10.29.8.3) with the Ranging Control Information field set according to Table 10-151. This frame and its acknowledgment define the first round-trip time measurement, while the RRMC IE delivery in the MCPS-DATA.indication primitive tells the next higher layer to initiate the second round-trip time measurement of the exchange by the sending of a Data frame in the other direction. This Data frame includes an RRMC IE with the Ranging Control Information field set according to Table 10-151 to indicate this is the continuation of the exchange and both of the Reply Time Request and Round-trip Time Request fields set to one to request the reply time and the result of the first round-trip time measurement. The acknowledgment to this message completes the second round-trip time measurement. A subsequent message from the initiator conveys the first round-trip time measurement and the reply time for the second round-trip time measurement in an RMI IE (described in 10.29.8.4). Figure 10-206 shows the message sequence chart for this exchange. In the figure the designation RRMC IE (2) means an RRMC IE with its Ranging Control Information field set to two, and designation RRMC IE (3) means an RRMC IE with its Ranging Control Information field set to three. When the responder receives the second MCPS-DATA.indication primitive (with the RMI IE), it has sufficient information to calculate the TOF between the two devices according to the formula given in 10.29.1.2.3. The subsequent reporting of the ranging result to the initiating end, using the RMI IE, depends on the value of the TOF Request field in the initiating RRMC IE.

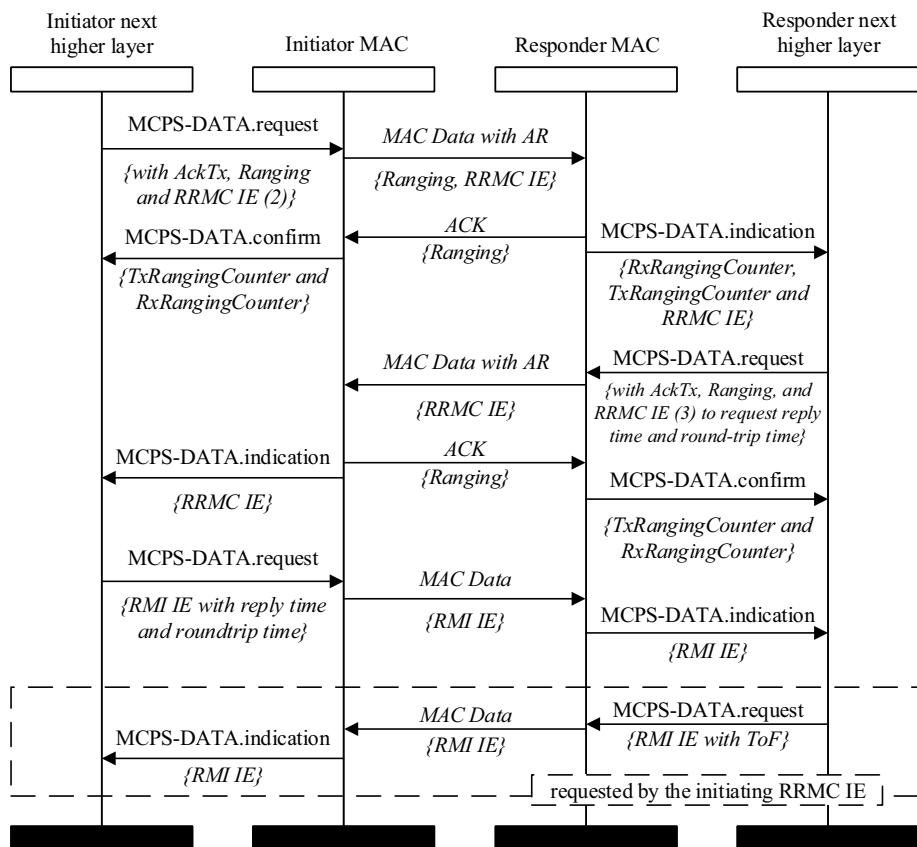


Figure 10-206—Message sequence chart for DS-TWR with deferred reply time result

10.29.6.7 Ranging procedure for DS-TWR with embedded ranging time information

To achieve the three-message DS-TWR exchange described in Figure 10-199 requires that the initiating end is able to embed the reply time as part of completing the second round-trip time measurement. With reference to the message sequence chart of Figure 10-207, the DS-TWR is initiated by an RFRAAME carrying an RRMC IE (described in 10.29.8.3) with its Ranging Control Information field set according to Table 10-151, and TOF Request field set to zero indicating that the initiating end does not require a report of the ranging. In the figure, the designation RRMC IE (2) means an RRMC IE with its Ranging Control Information field set to two, and designation RRMC IE (3) means an RRMC IE with its Ranging Control Information field set to three.

The responding side completes the first round-trip time measurement and initiates the second measurement with an RFRAAME carrying an RRMC IE with control field set according to Table 10-151 to indicate this is the continuation of the exchange and with the Reply Time Request field and Round-trip Time Request field both set to one, indicating requests for the first round-trip time measurement and the reply time for the second round-trip time measurement. The initiator completes the exchange by sending a final RFRAAME carrying the first round-trip time measurement in an RMI IE (described in 10.29.8.4) and the reply time of this second round-trip time measurement in an RTI IE (as described in 10.29.8.1).

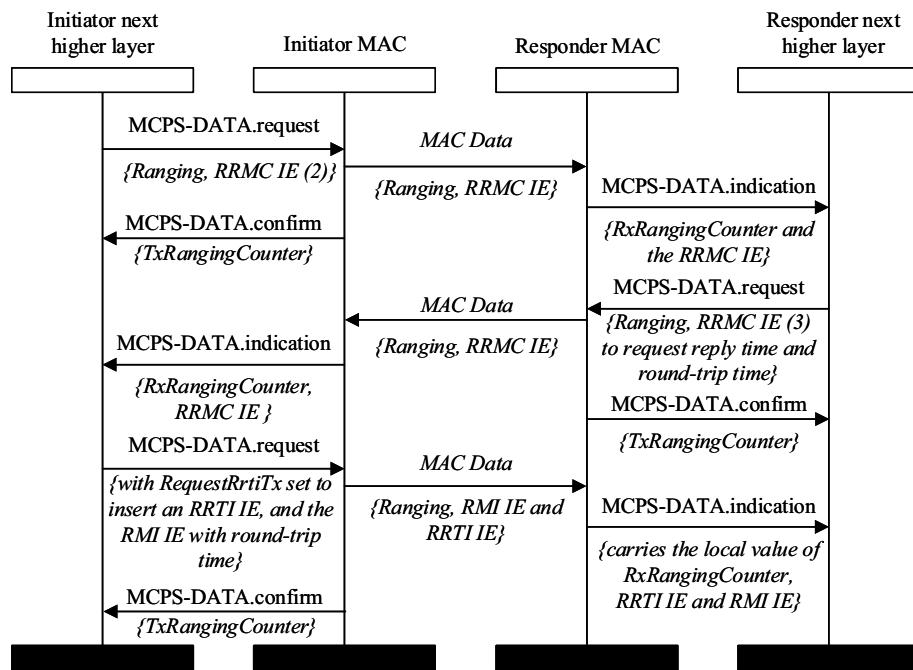


Figure 10-207—Message sequence chart for DS-TWR with three messages

When the responder higher layer receives the second MCPS-DATA.indication primitive, it has sufficient information to calculate the TOF between the two devices according to the formula given in 10.29.1.2.3. When the initiator of the ranging exchange wants the result, it will set the TOF Request field of the initiating RRMC IE, to ask the responding end to convey the result in an RMI IE in a subsequent message at the end of the exchange as shown in Figure 10-206.

10.29.6.8 Other procedures for coordinating RDEV and ERDEV

For successful interworking of HRP-ERDEV when an STS is being employed, the transmitter and receiver need to be aligned with respect to the seed (i.e., STS seed and data value V) used in the transmitter to generate the STS and used in the receiver to generate the sequence to correlate with the received STS. To coordinate these values, the secure private data communication capability of this standard may be used to transfer the seed between devices using the Ranging STS Seed and Data IE (RSSD IE) as described in 10.29.8.2. The counter value within the RSSD IE can relate to the current packet or a future one, as is indicated by the cyclic prefix (CP) field of the IE. The higher layer is responsible for using the received RSSD IE information to configure the STS seed, (via *phyHrpUwbStsSeed*, *phyHrpUwbStsVUpper96*, and *phyHrpUwbStsVCounter* PIB attributes), appropriately for its future packet transmissions and receptions. A header IE version of the RSSD IE is also defined, in 10.29.7.1, to facilitate synchronization of STS generators using information sent in the clear while accompanied by secured payload IEs and data.

When receiving a frame that contains an RSSD IE header IE, it is intended that the IE is delivered to the next higher layer to allow it to set the *phyHrpUwbStsSeed*, *phyHrpUwbStsVUpper96*, and *phyHrpUwbStsVCounter* attributes appropriately for STS generation. If a frame containing an RSSD IE header IE fails to pass the incoming security processing, for example if the receiver does not have the key to validate the MIC, the RSSD IE shall be delivered to the next higher layer via the HeaderIEList parameter of the MLME-COMM-STATUS.indication.

Similarly, when using DPS as described in 10.29.4, the RDEVs need to coordinate the preamble codes and channel selection they are going to employ and again the secure private data communication capability of this standard can be used to transfer the selected preamble code indices and channel number values between devices using the RCPCS IE (as described in 10.29.8.5).

10.29.7 Header IEs for ranging

10.29.7.1 Ranging STS Seed and Data IE (RSSD IE)

The RSSD IE header IE content is formatted exactly the same as the RSSD IE payload IE specified in 10.29.8.2. This header IE facilitates synchronization of STS generators using information sent in the clear, while accompanied by secured payload IEs and data.

10.29.8 Nested IEs for ranging

10.29.8.1 Ranging Reply Time Instantaneous IE (RRTI IE)

The RRTI IE conveys the reply time(s) of the response frame containing the RRTI IE typically with respect to one or more frames containing an RRMC IE (as described in 10.29.8.3) with the Reply Time Request field value set to one to solicit this response. The node(s) to address in the RRTI IE, and the reference time(s) with respect to which the reply time(s) in the RRTI IE are referenced, are specified via the RequestRrtiTxList in the DataRequestRangingDescriptor parameter of the MCPS DATA.request primitive. The Content field of the RRTI IE shall be formatted as shown in Figure 10-208.

Bits: 0–1	2–7	Octets: variable
Address Size Specifier	RRTI List Length	RRTI List

Figure 10-208—RRTI IE Content field format

The Address Size Specifier field specifies the size of the addresses used in the RRTI List field, as per the definition in Table 10-149.

Table 10-149—Address Size Specifier field values

Address Size Specifier field value b1 b0	Address Size
00	Zero octets, no addresses present
01	Reserved
10	Two octets, short addresses (16 bit)
11	Eight octets, extended addresses (64 bit)

The RRTI List Length field specifies the number of elements in the RRTI List field.

The RRTI List field contains RRTI List elements, each of which is structured as per Figure 10-209.

Octets: 4	0/2/8
RX-to-TX Reply Time	Address

Figure 10-209—RRTI List element format

The RX-to-TX Reply Time field is an unsigned integer giving the difference between a reference time specified by the higher layer and the transmit time of the response RFRAME containing the RRTI IE. Typically, the reference time used with respect to a particular source is the receive time of an RFRAME from that source that contains an RRMC IE with Reply Time Request field set to one. The reference for these time values is the RMARKER. The units of time are specified in 10.29.1.4. The general procedures for using the RRTI IE are specified in 10.29.6.

The Address field, if present, is supplied by the next higher layer, and is typically the address of the device that sent the RRMC IE requesting the reply time.

For unicast ranging between one initiator and one responder, the Address field shall be omitted since it is specified by the Destination Address field of the MAC header. For scheduled multi-node ranging, the Address field may be omitted if the reply times to different RDEVs are stacked in a pre-negotiated order.

The use of the RRTI IE is only appropriate where the sending device is able to accurately pre-determine the transmission time of the frame containing the IE, complete the calculations of time duration between the upcoming transmission and the specified reference time for the frame being responded to, and insert the RRTI IE into the transmitted frame.

10.29.8.2 Ranging STS Seed and Data IE (RSSD IE)

The RSSD IE can be used to convey and align the seed, (i.e., STS seed and data), used for STS generation. The Content field of the RSSD IE shall be formatted as shown in Figure 10-210.

Bits: 0	1	2	3	4	5–6	7	Octets: 0/4	0/4	0/4	0/4	0/16	0/4/8/16
V3P	V2P	V1P	VCP	SSP	ACP	CP	V3	V2	V1	V Counter	STS Seed	Application Code

Figure 10-210—RSSD IE Content field format

The V3P field value of one indicates the presence of the V3 field, and the value zero means it is not present.

The V2P field value of one indicates the presence of the V2 field, and the value zero means it is not present.

The V1P field value of one indicates the presence of the V1 field, and the value zero means it is not present.

The VCP field value of one indicates the presence of the V Counter field, and the value zero means it is not present.

The SSP field value of one indicates the presence of the STS Seed field, and the value zero means it is not present.

The ACP field indicates the presence of the Application Code field as per Table 10-150.

Table 10-150—Values of the ACP field in the RSSD IE

ACP field value	Meaning
0	The Application Code field is not present in the RSSD IE
1	A 4-octet Application Code field is present in the RSSD IE
2	An 8-octet Application Code field is present in the RSSD IE
3	A 16-octet Application Code field is present in the RSSD IE

The CP field value of one means the V Counter field (if present) applies to the current packet. A CP field value of zero means that the RSSD IE applies to a future packet exchange.

The V3 field, if present, contains a 4-octet string to set bits 96 to 127 of the STS generation data.

The V2 field, if present, contains a 4-octet string to set bits 64 to 95 of the STS generation data.

The V1 field, if present, contains a 4-octet string to set bits 32 to 63 of the STS generation data.

The V Counter field, if present, contains a 4-octet string to set the counter portion of the STS generation data.

The V Counter, V1, V2, and V3 fields can be transmitted separately to facilitate synchronization between ranging nodes.

The STS Seed field, if present, contains a 16-octet string to initialize the STS seed.

The Application Code field, if present, provides a mechanism for the next higher layer to transfer additional application specific information relating to the use of the IE content. The Application Code field content is defined by the higher layers. The presence and length of the Application Code field is determined by the ACP field as per Table 10-150.

The fields of the RSSD IE are determined and consumed by the next higher layer. The next higher layer is responsible for validating these as necessary and programming the *phyHrpUwbStsSeed*, *phyHrpUwbStsVUpper96*, and *phyHrpUwbStsVCounter* PIB attributes accordingly.

The STS Seed field and the V3, V2, V1, and V Counter fields that together define the seed for STS generation are strings of octets and as such are sent in the octet order typical for any string. When treating these as numbers in the context of Figure 16-11, the octet received first in time is the treated as the most significant octet.

In the case that the contents of the RSSD IE are confidential, its security level shall be 5 or higher.

10.29.8.3 Ranging Request Measurement and Control IE (RRMC IE)

The RRMC IE can be used to send ranging requests to a selected set of devices and to control ranging procedures. The Content field of the RRMC IE shall be formatted as shown in Figure 10-211.

Bits: 0	1	2	3	4	5–6	7	Octets: 0/1	variable
Reply Time Request	Round-trip Time Request	TOF Request	AOA Azimuth Request	AOA Elevation Request	Ranging Control Information	Address Size	RMCC Address List Length	RMCC Address List

Figure 10-211—RRMC IE Content field format

The Reply Time Request field when one indicates that the reply time is requested, or is not requested when this field is zero.

The Round-trip Time Request field when one indicates that the round-trip time measurement is requested, or is not requested when this field is zero.

The TOF Request field when one indicates that the TOF ranging result is requested, or is not requested when this field is zero.

The AOA Azimuth Request field when one indicates that an AOA in azimuth measurement is requested, or is not requested when this field is zero.

The AOA Elevation Request field when one indicates that an AOA in elevation measurement is requested, or is not requested when this field is zero.

The Ranging Control Information field shall have one of the values defined in Table 10-151, to indicate the function of the frame as described in the procedures defined in 10.29.6 and 10.32.

Table 10-151—Values of the Ranging Control Information field in the RRMC IE

Ranging Control Information field value	Meaning
0	This frame is the ranging initiation message for SS-TWR.
1	This frame is responding to the ranging initiation message of SS-TWR.
2	This frame is the ranging initiation message for DS-TWR.
3	This frame is continuing the DS-TWR, initiating the second round-trip time measurement.

The Address Size field specifies the size of the addresses used in the RRMC Address List field. If the Address Size field is zero, all addresses in the RRMC Address List elements are short addresses. If the Address Size field is one, all addresses are extended addresses.

The RRMC Address List Length field indicates the number of addresses in the Address RRMC Address List field. This field may be omitted when no addresses are provided, for example in unicast ranging where the target device is identified by the destination address in the MHR.

The RRMC Address List field contains a list of addresses to which the RRMC IE is directed. All addresses in the list shall be the size specified by the Address Size field of the RRMC IE.

If the RRMC IE is conveyed in a unicast Data frame, then since the destination address is specified by the MHR, the RRMC Address List Length and RRMC Address List fields are not needed.

When the RRMC IE is in a broadcast message the RRMC Address List Length and RRMC Address List fields may also be omitted if the sender intends to direct the request to all devices receiving it. However, if the sender wants responses from a specified set of devices, the RRMC Address List Length and RRMC Address List fields are used to select the set of devices to respond.

In SS-TWR, the initiator typically calculates the TOF. As shown in Figure 10-235, the responder can request the resultant TOF by including, in its response, an RRMC IE with the TOF Request field set.

In DS-TWR, the responder typically calculates the TOF. As shown in Figure 10-239, the initiator can request the resultant TOF by including an RRMC IE in either of the two messages it sends to perform the DS-TWR exchange.

When a device wishes to request different information from different responding devices, multiple RRMC IEs can be included in a single broadcast message, each requesting the desired set of parameters from the appropriate set of responding devices.

10.29.8.4 Ranging Measurement Information IE (RMI IE)

The RMI IE can be used to send ranging-related measurements to one or more devices. The Content field of the RMI IE shall be formatted as shown in Figure 10-212.

Bits: 0	1	2	3	4	5	6–7	8	9–15	Octets: variable
Reply Time Present	Round-trip Time Present	TOF Present	AOA Azimuth Present	AOA Elevation Present	AOA FOM Present	Address Size Specifier	Deferred Mode	RMI List Length	RMI List

Figure 10-212—RMI IE Content field format

The Reply Time Present field when one indicates that the RX-to-TX Reply Time field is present in each RMI List element, or when zero that it is not present.

The Round-trip Time Present field when one indicates that the TX-to-RX Round-trip Time field is present in each RMI List element, or when zero that it is not present.

The TOF Present field when one indicates that the TOF field is present in each RMI List element, or when zero that it is not present.

The AOA Azimuth Present field when one indicates that the AOA Azimuth field is present in each RMI List element, or when zero that it is not present.

The AOA Elevation Present field when one indicates that the AOA Elevation field is present in each RMI List element, or when zero that it is not present.

The AOA FOM Present field when one indicates that the AOA Azimuth FOM field is present in each RMI List element if the AOA Azimuth field is present and that the AOA Elevation FOM field is present in each

RMI List element if the AOA Elevation field is present, or when zero that neither the AOA Azimuth FOM field nor the AOA Elevation FOM field are present.

The Address Size Specifier field specifies the size of the addresses used in the RMI List field, as per the definition in Table 10-149.

The Deferred Mode field when zero indicates that this RMI IE is embedded in the RFRAME, or when one that this RMI IE is conveyed in a deferred message, that is in a later measurement report phase.

The RMI List Length field specifies the number of elements in the RMI List field, each of which shall be formatted as shown in Figure 10-213.

Octets: 0/4	0/4	0/4	0/2	0/1	0/2	0/1	0/2/8
RX-to-TX Reply Time	TX-to-RX Round-trip Time	TOF	AOA Azimuth	AOA Azimuth FOM	AOA Elevation	AOA Elevation FOM	Address

Figure 10-213—RMI List element format

The RX-to-TX Reply Time field is an unsigned integer that conveys the time difference between the receive time of the RFRAME being responded to and the transmit time of the response RFRAME.

The TX-to-RX Round-trip Time field is an unsigned integer that conveys the time difference between the transmit time of the RFRAME initiating a round-trip time measurement and the receive time of the response RFRAME from the addressed source (see Address field description) that completes the round-trip time measurement. The units of time are specified in 10.29.1.4.

The TOF field is an unsigned integer that conveys the TOF estimate between the sending device and the addressed device (see Address field description). The units of time are specified in 10.29.1.4.

The AOA Azimuth field is a signed integer reporting the estimated AOA in the azimuth measured with respect to the addressed device (see Address field description). The unit is $2\pi/(2^{16} - 1)$, with 0 radians being directly in front of the sending device.

The AOA Azimuth FOM field is an unsigned integer that conveys the reliability of the estimated AOA in the azimuth. Higher AOA Azimuth FOM field values indicate better quality AOA estimates, and an AOA Azimuth FOM field value of zero means that the AOA Azimuth estimate is invalid.

The AOA Elevation field is a signed integer reporting the estimated AOA in the elevation measured with respect to the addressed device (see Address field description). The unit is $\pi/(2^{16} - 1)$, with 0 radians being in the horizontal plane of the sending device.

The AOA Elevation FOM field is an unsigned integer that conveys the reliability of the estimated AOA in the elevation. Higher AOA Elevation FOM field values indicate better quality AOA estimates, and an AOA Elevation FOM field value of zero means that the AOA Elevation estimate is invalid.

For the AOA Azimuth FOM field value and AOA Elevation FOM field value to be meaningful, the AOA capabilities of the measuring device including details of its antenna array setup need to be known. Agreeing and communicating these system parameters is beyond the scope of this standard. Out-of-band mechanisms as well as custom messages can be used for this purpose.

At least one measurement shall be present in the RMI IE.

The Address field, if present, specifies the device that the measurements in this RMI List element relate to. When the RMI IE is conveyed in a unicast Data frame, then the destination address specified by the MHR identifies the device and a single RMI List element without Address field shall be present in the IE. When the RMI IE is conveyed in a broadcast Data frame, then the Address field shall be present in each RMI List element. The size of the Address field is specified by the Address Size Specifier field value of the RMI IE.

The general procedures for using the RMI IE are specified in 10.29.6, 10.31, and 10.32.

10.29.8.5 Ranging Channel and Preamble Code Selection IE (RCPCS IE)

The RCPCS IE is provided as a mechanism to signal the choice of channel and/or choice of transmit and receive preamble codes for DPS as described in 10.29.4.1, for a forthcoming ranging exchange. The Content field of the RCPCS IE shall be formatted as shown in Figure 10-214.

Bits: 0	1	2	3–7	Octets: 0/4	0/3	0/1	0/1	0/2
CCIP	DDP	PSP	Channel Number	CCI	DPS Duration	TX Preamble Code	RX Preamble Code	PSR

Figure 10-214—RCPCS IE Content field format

The CCIP field when one indicates the presence of the CCI field, or when zero that it is not present.

The DDP field when one indicates the presence of the DPS Duration field, or when zero that it is not present.

The PSP field when one indicates the presence of the preamble sequence selection fields, that is the TX Preamble Code field, the RX Preamble Code field, and the PSR field.

The Channel Number field indicates the UWB channel number, that is as per 11.1.3.5 for the HRP UWB PHY and 11.1.3.8 for the LRP UWB PHY, for the forthcoming ranging exchange.

The CCI field specifies the channel configuration interval, which is the time in RSTU (as defined in 10.29.1.5) between the sending of this IE and reconfiguration to the specified channel.

The DPS Duration field specifies the effective time duration of the dynamic channel and preamble code selection, in units of RSTU for the ERDEV and symbols for non-ERDEV.

The TX Preamble Code field indicates the DPS preamble code that the IE sender will use for transmission during the forthcoming ranging exchange.

The RX Preamble Code field indicates the DPS preamble code that the IE sender will use for reception during the forthcoming ranging exchange.

Both these preamble codes shall be selected from Table 16-8, or both from Table 16-9.

The PSR field indicates the number of preamble symbol repetitions (PSR) to be used for the SYNC of each RFRAME of the forthcoming ranging exchange. This shall be one of the SYNC lengths specified in 16.2.6.2, or zero indicating no change in SYNC length is required.

The use of this IE is optional and it is the responsibility of the higher layer to apply the requisite settings using the MLME-DPS.request and MLME-SET.request primitives.

10.29.8.6 Ranging Reply Time Negotiation IE (RRTN IE)

The RRTN IE may be used to negotiate and communicate the value of the fixed reply time, and also to notify the ability of an RDEV to send a ranging response that can employ the RRTI IE (described in 10.29.8.1) and convey its preferred reply time for such a ranging response. This is applicable in both SS-TWR and DS-TWR ranging exchanges. The Content field of the RRTN IE shall be formatted as shown in Figure 10-215.

Bits: 0–3	4–7	Octets: 0/4	0/2
Type	Reserved	Reply Time	Precision

Figure 10-215—RRTN IE Content field format

The Type field specifies the function of the IE with respect to the reply time, as per Table 10-152.

Table 10-152—Values of the Type field in the RRTN IE

Type field value	Meaning
0	This RRTN IE is requesting disabling the fixed reply time from the responding device. In this case the Reply Time and Precision fields are not present.
1	This is indicating (in response to an RRTN IE with Type value of zero) that the fixed reply time functionality in the sending device has been disabled as requested. In this case the Reply Time and Precision fields are not present.
2	This RRTN IE is requesting the use of a fixed reply time from the responding device. In this case, the Reply Time field is present and indicates the fixed reply time that the sending (initiator device) would prefer, and the Precision field is not present.
3	This is in response to an RRTN IE of Type two to indicate that the sending device cannot support fixed reply time as a responding device. In this case the Reply Time and Precision fields are not present.
4	This is in response to an RRTN IE of Type two to indicate that the sending device cannot support the requested reply time, in which case the Reply Time and Precision fields are present and indicate the fixed reply time capability that the device can support.
5	This is in response to an RRTN IE of Type two to confirm that it will respond with a fixed reply time. In this case the Reply Time and Precision fields shall be present and contain the values to be used by the responding device.
6	This RRTN IE is indicating the RDEV's ability to employ the RRTI IE (described in 10.29.8.1) in a ranging response. In this case the Reply Time field shall contain the preferred reply time for the ranging response, that is the time the RDEV needs to generate the response with the RRTI IE. The Precision field shall not be present.
7–15	Reserved.

The Reply Time field specifies the desired, supported, or selected reply time, depending on the Type field per Table 10-152. Where this is the supported fixed reply time value (i.e., Type field is four) the responding

node may be able to support a larger fixed reply time, a capability that the initiator can discover by requesting a larger time.

The Precision field indicates the degree of control that the responder has on its fixed reply time responses, that is the actual fixed reply time that the responder can provide in good conditions has the indicated precision plus or minus with respect to the nominal fixed reply time.

The units of time of the Reply Time and Precision fields shall be as specified in 10.29.1.4. The Precision field cannot be present on its own, that is can only follow the Reply Time field.

The use of the RRTN IE to communicate the preferred reply time for RRTI IE is described in 10.29.6.4.

If a device is capable of a fixed reply time of sufficient precision, this information can be used to perform SS-TWR without needing to measure and send the reply time for every ranging exchange, as described in 10.29.6.5. Fixed reply times can also be used when performing DS-TWR.

10.29.9 MAC management service primitives for ranging

10.29.9.1 Primitives for specifying dynamic channel and preamble selection

10.29.9.1.1 General

These primitives are used by a device to enable or disable DPS as well as to define the value of dynamic preamble for transmission and reception for a given time. DPS is only supported by the HRP UWB PHY.

10.29.9.1.2 MLME-DPS.request

The MLME-DPS.request primitive allows the next higher layer to request that the PHY utilize a given pair of preamble codes and/or channel number temporarily overriding the *phyCurrentCode* and/or *phyCurrentChannelInfo* attribute settings.

The semantics of this primitive are as follows:

```
MLME-DPS.request ( 
    TxDpsIndex,
    RxDpsIndex,
    ChannelNumber,
    DpsDuration,
    ConfigTime
)
```

The primitive parameters are defined in Table 10-153.

If the ConfigTime parameter is provided and it specifies a time that is more than half a period of the RSTU time counter in the future, the MAC shall consider this to be a late invocation and shall immediately return an error status value of PAST_TIME in the MLME-DPS.confirm primitive.

This primitive may also be generated to cancel a previously generated request to enable dynamic preamble code and channel selection.

If the DpsDuration parameter is non-zero, the MLME starts a timer for this duration at the point when it applies the change to the selected preamble codes and/or channel number, that is at the time specified by the ConfigTime parameter. The MLME then issues the MLME-DPS.confirm primitive with the appropriate Status parameter.

Table 10-153—MLME-DPS.request parameters

Name	Type	Valid range	Description
TxDpsIndex	Integer	0, 13–16, 21–32	The index value for the transmitter. A value of zero disables the index and indicates that the <i>phyCurrentCode</i> value is to be used, as defined in 16.2.6.2. Other values indicate the preamble code, as defined in Table 16-8 and Table 16-9.
RxDpsIndex	Integer	0, 13–16, 21–32	The index value for the receiver. A value of zero disables the index and indicates that the <i>phyCurrentCode</i> value is to be used, as defined in 16.2.6.2. Other values indicate the preamble code, as defined in Table 16-8 and Table 16-9.
ChannelNumber	Integer	–1, 0–15	UWB channel as per 11.1.3.5 for the HRP UWB PHY and 11.1.3.8 for the LRP UWB PHY, for the forthcoming message exchanges. A value of minus one disables the channel selection and indicates that the <i>phyCurrentChannelInfo</i> value is to be used.
DpsDuration	Integer	0x000000–0xffffffff	When non-zero this specifies a timeout period, starting from the application of the DPS change, after which the MAC will issue an MLME-DPS.indication primitive. For non-ERDEV, this timeout period is specified in symbols, while for ERDEV, this time shall be in the unit of RSTU (as defined in 10.29.1.5). If the value is zero, then no MLME-DPS.indication will be generated. In either case, the DPS/DCS change persists until canceled by another MLME-DPS.request.
ConfigTime	Integer	0x000000–0xffffffff	Specifies a future time at which the MLME is to apply the specified DPS change with reference to the RSTU time counter (defined in 10.29.1.5). Typically, the ConfigTime value is calculated by adding the CCI field value conveyed by an RCPCS IE to the Timestamp reported by the MCPS-DATA.indication delivering the RCPCS IE, (or for the RCPCS IE sender, the Timestamp of the MCPS DATA.confirm). If the ConfigTime parameter is omitted the DPS configuration change is applied immediately.

If the DpsDuration timer is running, an MLME-DPS.indication is generated when the timer expires. The next higher layer is responsible for subsequently canceling or changing the DPS settings by issuing a further MLME-DPS.request.

If an MLME-DPS.request is issued to cancel the DPS before the expiration of the DpsDuration timer, the timer is stopped and no MLME-DPS.indication is generated.

10.29.9.1.3 MLME-DPS.confirm

The MLME-DPS.confirm primitive reports the results of the attempt to enable or disable the DPS/DCS.

The semantics of this primitive are as follows:

MLME-DPS.confirm
(
Status
)

The primitive parameter is defined in Table 10-154.

Table 10-154—MLME-DPS.confirm parameter

Name	Type	Valid range	Description
Status	Enumeration	SUCCESS, NOT_SUPPORTED	The result of the request to enable or disable dynamic preamble and/or channel.

The MLME-DPS.confirm primitive is generated by the MLME and issued to its next higher layer in response to an MLME-DPS.request primitive.

If any parameter in the MLME-DPS.request primitive is not supported or is out of range, the Status of NOT_SUPPORTED is returned. If the request to enable or disable the DPS/DCS was successful, the MLME issues the MLME-DPS.confirm primitive with a Status of SUCCESS.

10.29.9.1.4 MLME-DPS.indication

The MLME-DPS.indication primitive indicates the expiration of the DpsDuration timer if it is running. Issuing the MLME-DPS.request primitive to reset the dynamic preamble code and channel selection is the responsibility of the higher layer.

The semantics of this primitive are as follows:

MLME-DPS.indication ()

10.29.9.2 Primitives for channel sounding

10.29.9.2.1 General

These primitives are used to obtain the results of a channel sounding from an RDEV that supports the optional sounding capability.

For information on the use of the MLME-SOUNDING primitives, see section 7.1.1.4.5 of “Application of IEEE Std 802.15.4” [B4].

10.29.9.2.2 MLME-SOUNDING.request

The MLME-SOUNDING.request primitive is used by the next higher layer to request that the PHY respond with channel sounding information. The MLME-SOUNDING.request primitive shall be supported by all RDEVs; however, the underlying sounding capability is optional in all cases.

The semantics of this primitive are as follows:

MLME-SOUNDING.request ()

If the feature is supported, the MLME will respond with the MLME-SOUNDING.confirm to deliver the sounding information.

10.29.9.2.3 MLME-SOUNDING.confirm

The MLME-SOUNDING.confirm primitive reports the result of a request to the PHY to provide channel sounding information. The MLME-SOUNDING.confirm primitive shall be supported by all RDEVs; however, the underlying sounding capability is optional in all cases.

The semantics of this primitive are as follows:

```
MLME-SOUNDING.confirm      (
    SoundingList,
    Status
)
```

The primitive parameters are defined in Table 10-155.

Table 10-155—MLME-SOUNDING.confirm parameters

Name	Type	Valid range	Description
SoundingList	List of sounding points	—	Results of the sounding measurement.
Status	Enumeration	SUCCESS, NO_DATA, UNSUPPORTED_ATTRIBUTE	The status of the attempt to return sounding data.

The elements of a SoundingList are defined in Table 10-156.

Table 10-156—Elements of a SoundingList

Name	Type	Valid range	Description
SoundingTime	Signed integer	—	The LSB represents a nominal 16 ps. (see NOTE).
SoundingAmplitude	Signed integer	—	A relative measurement or the received signal strength.
NOTE—Each element of the <i>SoundingList</i> contains a <i>SoundingTime</i> and a <i>SoundingAmplitude</i> . The <i>SoundingTime</i> is a signed integer, and the LSB for the HRP UWB PHY represents a nominal 16 ps (2^{-7} of a chip time), and for the LRP UWB PHY 1 ps (2^{-20} of a chip time). The <i>SoundingAmplitude</i> is a signed integer representing a relative measurement. The <i>SoundingAmplitudes</i> have no absolute meaning, only a relative meaning.			

If the channel sounding information is available, the Status parameter will be set to SUCCESS, and the SoundingList will contain valid data.

If the MLME-SOUNDING.request primitive is received when there is no information present, e.g., when the PHY is in the process of performing a measurement, the Status parameter will be set to NO_DATA.

If the channel sounding capability is not supported by the PHY, the Status parameter will be set to UNSUPPORTED_ATTRIBUTE.

10.29.9.3 Primitives for ranging calibration

10.29.9.3.1 General

These primitives are used to obtain the results of a ranging calibration request from an RDEV.

For information on the use of the MLME-CALIBRATE primitives, see section 7.1.1.6 of “Application of IEEE Std 802.15.4” [B4].

10.29.9.3.2 MLME-CALIBRATE.request

The MLME-CALIBRATE.request primitive attempts to have the PHY respond with RMARKER offset information. The MLME-CALIBRATE.request primitive shall be implemented by RDEVs.

The semantics of this primitive are as follows:

MLME-CALIBRATE.request ()

The MLME issues the MLME-CALIBRATE.confirm primitive with the appropriate information.

10.29.9.3.3 MLME-CALIBRATE.confirm

The MLME-CALIBRATE.confirm primitive reports the result of a request to the PHY to provide internal propagation path information. The MLME-CALIBRATE.confirm primitive shall be implemented by RDEVs.

MLME-CALIBRATE.confirm (CalTxRMarkerOffset,
CalRxRMarkerOffset,
Status)

The primitive parameters are defined in Table 10-157.

Table 10-157—MLME-CALIBRATE.confirm parameters

Name	Type	Valid range	Description
CalTxRMarkerOffset	Unsigned Integer	0x00000000–0xffffffff	A count of the propagation time from the ranging counter to the transmit antenna. For the HRP UWB PHY, the LSB of a time value represents 2^{-7} of a chip time at the mandatory chipping rate of 499.2 MHz. For the LRP UWB PHY, the LSB of a time value represents 2^{-20} of the base mode chipping rate of 1 MHz.
CalRxRMarkerOffset	Unsigned Integer	0x00000000–0xffffffff	A count of the propagation time from the receive antenna to the ranging counter. For the HRP UWB PHY, the LSB of a time value represents 2^{-7} of a chip time at the mandatory chipping rate of 499.2 MHz. For the LRP UWB PHY, the LSB of a time value represents 2^{-20} of the base mode chipping rate of 1 MHz.
Status	Enumeration	SUCCESS, NO_DATA, COMPUTATION_NEEDED, UNSUPPORTED_ATTRIBUTE	The status of the attempt to retrieve internal propagation path information from the PHY.

The MLME-CALIBRATE.confirm primitive is generated by the MLME and issued to its next higher layer in response to an MLME-CALIBRATE.request primitive.

If the feature is supported, the MLME issues the MLME-CALIBRATE.confirm primitive with a Status of SUCCESS.

If the MLME-CALIBRATE.request primitive is received when there is no information present, e.g., when the PHY is in the process of performing a measurement, the Status parameter will be set to NO_DATA.

If the PHY does not support autonomous self-calibration, the Status parameter will be set to a value of COMPUTATION_NEEDED. This indicates to the next higher layer that it should use the sounding primitives to finish the calibration.

If the channel sounding capability is not present in the PHY, the Status parameter will be set to a value of UNSUPPORTED_ATTRIBUTE.

10.29.9.4 Primitives for specifying STS parameters

10.29.9.4.1 MLME-STS.request

The MLME-STS.request primitive allows the next higher layer to request that the HRP-ERDEV utilizes a given set of STS parameters.

The semantics of this primitive are as follows:

```
MLME-STS.request ( TxStsPacketStructure,
                    TxStsSegmentLength,
                    TxStsNumberSegments,
                    RxStsPacketStructure,
                    RxStsSegmentLength,
                    RxStsNumberSegments )
```

The primitive parameters are defined in Table 10-158.

Table 10-158—MLME-STS.request parameters

Name	Type	Valid range	Description
TxStsPacketStructure	Integer	0–3	This specifies the STS packet structure to use in the transmitter. The values are defined in Table 16-1.
TxStsSegmentLength	Integer	0–4	This specifies the STS segment length to use in the transmitter. This is only meaningful when the TxStsPacketStructure parameter is non-zero. The values are defined in Table 16-18.
TxStsNumberSegments	Integer	0–3	This specifies the number of STS segments to use in the transmitter. The values are defined in Table 16-19. This is only meaningful when the TxStsPacketStructure parameter is non-zero.
RxStsPacketStructure	Integer	0–3	This specifies the STS packet structure to use in the receiver. The values are defined in Table 16-1.

Table 10-158—MLME-STS.request parameters (continued)

Name	Type	Valid range	Description
RxStsSegmentLength	Integer	0–4	This specifies the STS segment length to use in the receiver. This is only meaningful when the RxStsPacketStructure parameter is non-zero. The values are defined in Table 16-18.
RxStsNumberSegments	Integer	0–3	This specifies the number of STS segments to use in the receiver. The values are defined in Table 16-19. This is only meaningful when the RxStsPacketStructure parameter is non-zero.

This primitive may also be used to disable the use of STS in the transmitter and/or the receiver when the TxStsPacketStructure and/or RxStsPacketStructure parameters, respectively, are zero.

When the STS configuration attempt is successful the following attributes are updated accordingly:

- $\text{phyHrpUwbStsTxPacketConfig}$, $\text{phyHrpUwbStsTxSegLen}$, and $\text{phyHrpUwbStsTxSegNum}$,
 - $\text{phyHrpUwbStsRxPacketConfig}$, $\text{phyHrpUwbStsRxSegLen}$, and $\text{phyHrpUwbStsRxSegNum}$.

The result of the STS configuration attempt is reported by the MLME-STS.confirm primitive.

10.29.9.4.2 MLME-STS.confirm

The MLME-STS.confirm primitive reports the result of the attempt to configure the STS parameters via the MLME-STS.request primitive.

The semantics of this primitive are as follows:

MLME-STS.confirm
 (
 Status
)
)

The primitive parameter is defined in Table 10-159.

Table 10-159—MLME-STS.confirm parameter

Name	Type	Valid range	Description
Status	Enumeration	SUCCESS, INVALID_PARAMETER	This parameter reports the result of the MLME-STS.request attempt to configure STS parameters.

The MLME-STS.confirm primitive is generated by the MLME and issued to its next higher layer in response to an MLME-STS.request primitive.

If any parameter in the MLME-STS.request primitive is not supported or is out of range, the Status of INVALID_PARAMETER is returned.

If the request to configure the STS parameters was successful, the MLME issues the MLME-STS.confirm primitive with a Status of SUCCESS.

10.29.10 MAC constants and PIB attributes for ranging

Ranging attributes are described in Table 10-160. For explanation of dagger (\dagger) and asterisk (*) symbols see 8.4.3.1.

Table 10-160—Ranging mode related PIB attributes

Attribute	Type	Range	Description	Default
<i>macRangingSupported</i>	Boolean ^{*†}	TRUE, FALSE	This indicates whether the MAC sublayer supports the optional ranging features.	—

10.30 Ranging: Ranging in a PAN using superframe structure with ERDEV

10.30.1 Overview

The ranging time structure for ERDEV in a PAN using superframe structure is shown in Figure 10-216. The ranging time structure is characterized by repeating ranging beacons, where a ranging beacon is an Enhanced Beacon frame containing the Ranging Descriptor IE (RD IE) specified in 10.30.2.1.

The beacon interval of the ranging time structure is the time between two ranging beacons. The ranging time structure is composed of the ranging management period and the ranging period. The ranging management period is composed of ranging beacon slots (RBS). Each RBS has a duration specified in the ranging beacon (in multiples of the RSTU defined in 10.29.1.5). The RBS duration needs to be sufficient to allow transmission of a ranging beacon. The ranging beacon occupies RBS number zero. The ranging period consists of one or more ranging slots (see 10.32). The RD IE in the ranging beacon conveys the beacon interval value, information on the usage of the ranging management period, and the beginning of the ranging period.

The ranging management period may have one or more ranging contention access period(s) (RCAP) and one or more ranging contention free period(s) (RCFP). Each RCFP and RCAP is one or more RBS. The RCAP and RCFP may be interleaved in the ranging management period. The ranging management period may or may not be present in a given beacon interval. The channel access for slots in an RCAP is contention-based and for slots in an RCFP is schedule based.

The ranging period is structured as defined in 10.32.2 and 10.32.3. The ranging period begins with a ranging control message (RCM), which configures the ranging period. The ranging period may have more than one RCM. The ranging period may last until the next ranging beacon or could end before the next ranging beacon. The ranging period may or may not be present in a given beacon interval.

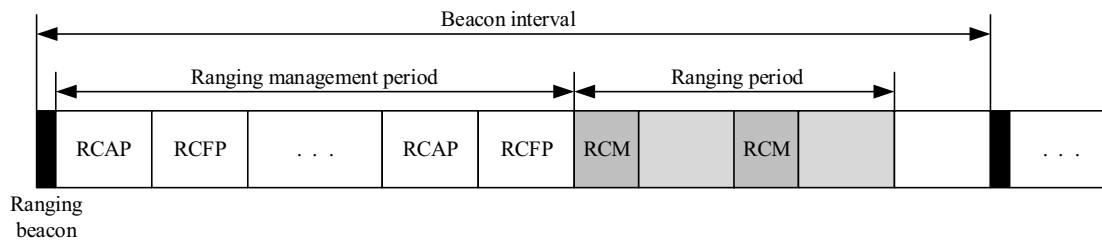


Figure 10-216—Ranging time structure for PAN using superframe structure with ERDEV

10.30.2 Nested IEs when doing ranging in a PAN using superframe structure with ERDEV

10.30.2.1 Ranging Descriptor IE (RD IE)

The RD IE is employed in Enhanced Beacon frames to specify the time structure for ranging. The Content field of the RD IE shall be formatted as shown in Figure 10-217.

Bits: 0	1–15	Octets: 2/4	2/4	1	variable
Beacon Interval Length	RBS Duration	Beacon Interval	First RCM Slot	RM Table Length	RM Table

Figure 10-217—RD IE Content field format

The Beacon Interval Length field when zero indicates that the Beacon Interval field and the First RCM Slot field are both two octets long, or when one that these two fields are both four octets long.

The RBS Duration field conveys the duration of the RBS in RSTU (as defined in 10.29.1.5).

The Beacon Interval field conveys the time period in RSTU between the start of the received packet (preamble) of the Enhanced Beacon frame carrying this RD IE and the start of the next such ranging beacon.

The First RCM Slot field conveys the ranging management period slot index where the first RCM is to be transmitted (effectively defining the end of the ranging management period). This shall be set to zero if the ranging period is not present in the current beacon interval. The first RCM occupies slot zero of the first ranging round of the ranging period.

The RM Table Length field specifies the number of elements in the RM Table field, each of which is formatted as per Figure 10-218 and which together define the usage of the ranging management period. The RM Table Length field shall be set to zero if the ranging management period is not present in the current beacon interval.

Bits: 0–10	11–21	22	23
RM Sub-period Start	RM Sub-period End	RM Sub-period Use	Reserved

Figure 10-218—RM Table element format

The elements of the RM Table that describe the ranging management period, shall define RCAP and RCFP as a sequential ordered set of contiguous, non-overlapping periods, ending immediately before the start of the ranging period as indicated by the First RCM Slot field.

The RM Sub-period Start field specifies the ranging management period slot number index beginning the sub-period being defined by this RM Table element row.

The RM Sub-period End field specifies the ranging management period slot number index ending the sub-period being defined by this RM Table element row.

The RM Sub-period Use field when one, indicates that the ranging management sub-period being defined by this RM Table element row is an RCFP, or when zero that it is an RCAP.

10.31 Ranging: Secure transactions

The enhanced ranging capabilities of the ERDEV can be used to protect transactions by using ranging to check that the distance between the communicating devices is as expected. In such secure service transaction scenarios, the higher layer is often interfacing between the radio and a secure element used in validating the transaction. When used for this purpose, the MPX IE shall be used as follows: (refer to Figure 9 of IEEE Std 802.15.9). The Transaction Control field consists of a 3-bit Transfer Type field and a 5-bit Transaction ID field.

The Transfer Type field shall be set to one (0b001) to indicate that the Multiplex ID associated with the dispatch code for the MPX IE is indicated by the Transaction ID field of the Transaction Control field. The Transaction ID field contains the five least significant bits of the Multiplex ID used as the dispatch code as defined in Table 20, of IEEE Std 802.15.9, and is used as an identifier to specify that this frame contains information used for Ranging Enhanced Secure Transactions.

The MPX IE with the dispatch code 0x0010, (16 decimal), for Ranging Enhanced Secure Service Transactions, is applicable to higher layer protocols that support transactions with a secure component in the device. When an MPX IE with the Transaction ID for Ranging Enhanced Secure Service Transactions is received in an RFRAIME, the MAC delivers it to the higher layer with an associated ranging measurement, which the higher layer can use to limit access based on range. When used for this purpose, the Upper-Layer Frame Fragment field of the MPX IE carries information to identify and distinguish transactions, with MAC payload used by the next higher layer to route the payload, and shall be formatted as shown in Figure 10-219. This information can be used by the respective device components (e.g., a secure element) to select the appropriate STS used for ranging. If a transaction takes place using multiple frames, all frames that transport data belonging to this particular transaction should include the MPX IE with the same Transaction ID and USSID value.

Bits: 0–2	3–5	6–10	11–15	Octets: variable	variable
Payload Type	Reserved	USSID Length	Additional Info Length	USSID	Additional Info

Figure 10-219—Format of Upper-Layer Frame Fragment field of MPX IE for Ranging Enhanced Secure Service Transactions

The Payload Type field specifies the type of the content contained in the MAC Payload field. The Payload Type field shall have one of the non-reserved values defined in Table 10-161.

Table 10-161—Values of Payload Type field

Payload Type field value	Meaning
0	Application specific payload.
1	MAC Payload field contains an APDU as defined by ISO/IEC 7816-4.
2	MAC Payload field contains a MIFARE Classic® command or response. ^a
3	MAC Payload field contains a MIFARE DESFire® command or response. ^b
4	MAC Payload field contains an Information field as defined by JIS X 6319-4.
5–7	Reserved.

^a MIFARE Classic is a registered trademark of NXP Semiconductors. This information is given for the convenience of users of this standard and does not constitute an endorsement by the IEEE of these products. Equivalent products may be used if they can be shown to lead to the same results.

^b MIFARE DESFire is a registered trademark owned by NXP Semiconductors. This information is given for the convenience of users of this standard and does not constitute an endorsement by the IEEE of these products. Equivalent products may be used if they can be shown to lead to the same results.

The USSID Length field specifies the number of octets in the USSID field. The valid range for USSID Length shall be 0 to 16.

The USSID field is used to identify and distinguish transactions. All frames that transport data belonging to the same transaction should use the same USSID value. The content of the USSID field depends on the Payload Type as per Table 10-162. It is impossible to support differentiation of transactions with the same Payload Type value unless a USSID is provided. The USSID field includes an ID that identifies the target application for the transaction.

Table 10-162—Permissible USSID depending on Payload Type field in Secure Service IE

Payload Type field value	Permissible content of the USSID Length and USSID fields
0	Either the USSID field contains an application specific payload info or the USSID Length field is set to zero.
1	Either the USSID field contains an application identifier (AID) formatted as specified in Figure 10-220 or the USSID Length field is set to zero, in which case the transaction is assumed to use implicit selection as defined in ISO/IEC 7816-4.
2	USSID Length field is set to zero.
3	Either the USSID field contains an AID formatted as specified in Figure 10-220 or the USSID Length field is set to zero.
4	The USSID Length field is set to two and the USSID field contains a system code (SC) formatted as specified in Figure 10-221.

The AID is an Application Identifier as defined in ISO/IEC 7816-5.

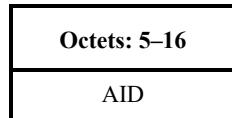


Figure 10-220—Format of USSID field when carrying an AID

The SC is a system code as defined by JIS X 6319-4.

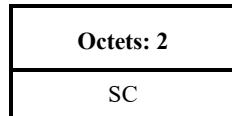


Figure 10-221—Format of USSID field when carrying an SC

The Additional Info Length field is an unsigned integer that specifies the number of octets in the Additional Info field.

The Additional Info field is used to provide a summary of the transaction, which can be used for user information and authorization. If present, the Additional Info field contains a string that can be used to provide additional information to the higher layer about the transaction to be performed. The encoding of characters into the Additional Info field follows UTF-8 in IETF RFC 3629 [B15]. Line breaks in the string are represented using a carriage return (CR) followed by a line-feed (LF), that is 0x0d, 0x0a in UTF-8. The Additional Info field should be present in the first frame used by a transaction.

10.32 Ranging: Multi-node ranging

10.32.1 Introduction

The use and support of the procedures and associated IEs in this subclause are optional. An RCM is a Data frame conveying the Advanced Ranging Control IE (ARC IE) described in 10.32.9.1. The RCM can be used to convey ranging parameters to control and configure aspects of the ranging procedure(s) such as the timeslot structure shown in Figure 10-223, the ranging methods specified in 10.29.1.2, and the STS packet configuration as specified in 16.2.

The following nomenclature is used for ERDEVs:

- Controller: An ERDEV that controls the ranging and defines the ranging parameters by sending an RCM.
- Controlee: An ERDEV that utilizes the ranging parameters received from the controller in the RCM.
- Initiator: An ERDEV that following the RCM, initiates a ranging exchange by sending the first message of the exchange, the ranging initiation message. A controller or a contreele can be an initiator.
- Responder: An ERDEV that responds to the ranging initiation message received from the initiator.

These terms are illustrated in Figure 10-222.

The next higher layer of the controller is responsible for determining the ranging parameters and the role of the participating ERDEVs as either initiators or responders. Unless it is otherwise specified that the MAC is

acting, the terms controller and conteree refer to those entities' next higher layer being informed of the event or taking the action being described.

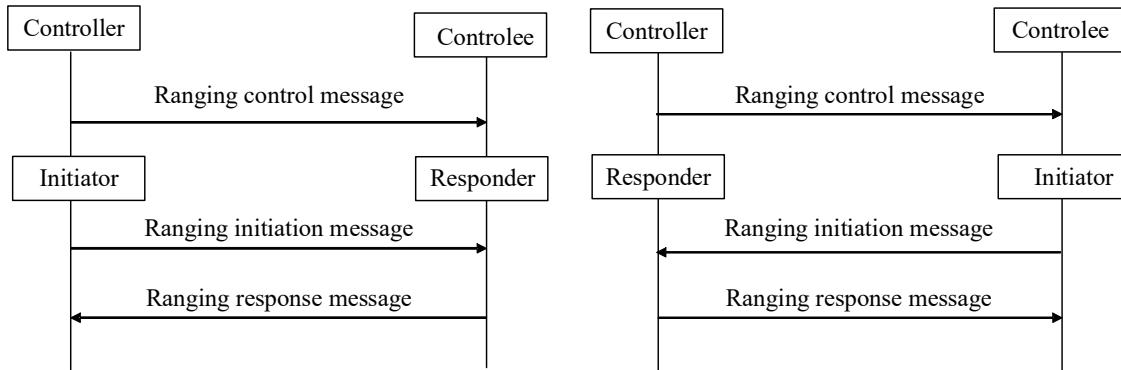


Figure 10-222—Ranging controller, conteree, initiator, and responder

Multi-node ranging is a ranging procedure in which one or more initiators perform ranging with a number of responders. There are two types of multi-node ranging, as indicated by the Schedule Mode field of the ARC IE defined in 10.32.9.1. The first type is time-scheduled ranging in which the controller knows the identities of all conterees and specifies the precise schedule of ranging transmissions. The second type is contention-based ranging in which the controller may not know the number or identities of the conterees, and hence the ERDEVs contend with each other.

NOTE—In the case of contention-based ranging, collision between responding devices is possible; the upper layer is responsible for filtering out inaccurate or wrong ranging results.

For time-scheduled ranging, the controller uses the Ranging Device Management IE (RDM IE) defined in 10.32.9.8 to select the participating ranging devices, specify their role as either initiator or responder, and assign their time slots. The RDM IE can be omitted from the RCM in the case where the roles and transmission schedule is pre-determined or conveyed via some out-of-band mechanism.

For contention-based ranging, the ERDEVs, that is initiator or responder devices, contend to transmit in the appropriate time slots. The Ranging Contention Phase Structure IE (RCPS IE), defined in 10.32.9.5, is used to specify different phases (see 10.32.2) for initiators and responders to contend, which can be conveyed in the RCM (in addition to the ARC IE). To provide for relative fairness among contending ERDEVs, the maximum number of attempts in a set of ranging round(s) specified by the same RCM is determined by the next higher layer of the controller. This information may be exchanged by the Ranging Contention Maximum Attempts IE (RCMA IE), as described in 10.32.9.6, in the RCM. Furthermore, if the controller knows the identities of the conterees, the RDM IE can be used to allocate ranging roles, that is initiator or responder, among ERDEVs.

10.32.2 Ranging block and round structure

A ranging block is a time period for ranging. Each ranging block consists of a whole number of ranging rounds, where a ranging round is a period of sufficient duration to complete one entire range-measurement cycle involving the set of ERDEVs participating in the ranging exchange. Each ranging round is further subdivided into an integer number of ranging slots where a ranging slot is a time period of sufficient duration for the transmission of at least one RFRAFME. Figure 10-223 shows the ranging block structure. In this figure, the ranging block is divided into N ranging rounds, each consisting of M ranging slots. The slot duration and the number of slots making up a ranging round can be changed between ranging rounds. This

can be achieved by the controller sending an RCM with the modified ranging round configuration whenever a change is required.

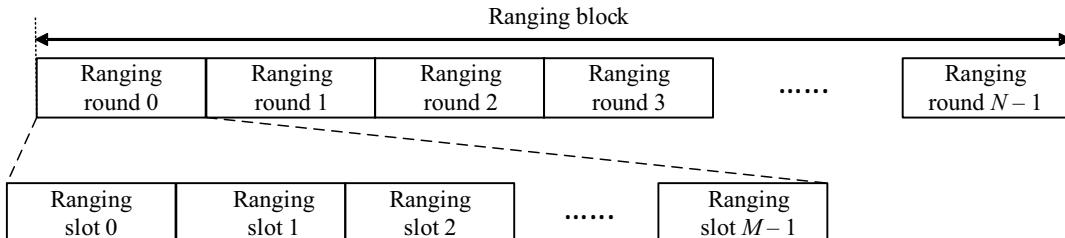


Figure 10-223—Illustration of ranging block, ranging round, and ranging slot

The time unit used in specifying the duration of ranging block, ranging round, and ranging slot is the RSTU as specified in 10.29.1.5. Ranging devices shall realize this ranging block structure such that the tolerance in the ranging block duration with respect to the PHY clock shall be within ± 100 ppm.

The following nomenclature is used for messages:

- Ranging control message (RCM): A message transmitted by a controller in slot zero, the first slot of a ranging round to configure ranging parameters.
- Ranging control update message (RCUM): A message transmitted by the controller at the last slot of ranging round(s) specified by the RCM to update ranging parameters for the next ranging round(s). The RCUM may include any of the IEs employed by the RCM, to give updates to the values of the parameters conveyed.
- Ranging interval update message (RIUM): A message transmitted by the controller between ranging blocks to update the intervals and also to help the synchronization between the participating ERDEVs. As described in 10.32.3.2, the RCUM conveys the scheduled time of the first RIUM, while the RIUM may convey the scheduled time of the next RIUM (if used) before the next ranging block starts.

The following nomenclature is used to describe the functionalities of different exchanges in a ranging round:

- Ranging control phase (RCP): A phase in which the controller sends an RCM.
- Ranging initiation phase (RIP): A phase in which the initiator(s) sends ranging initiation message(s) to the responder(s).
- Ranging response phase (RRP): A phase in which the responder(s) send their response message(s) to the initiator.
- Ranging final phase (RFP): A phase in which the initiator sends ranging final message(s) to the responder(s). This phase is only used for DS-TWR.
- Ranging phase (RP): A phase that should comprise RIP, RRP, and maybe RFP.
- Measurement report phase (MRP): A phase in which participating ERDEVs exchange ranging measurements and related service information.
- Ranging control update phase (RCUP): A phase in which the controller sends RCUM. If present, this phase shall be at the last slot of a set of ranging rounds specified by the RCM.
- Ranging interval update phase (RIUP): A phase in which the controller sends RIUM.

In a ranging round SS-TWR or DS-TWR can be used for ranging and localization as described in 10.32.4 to 10.32.8, or OWR may be used as described in 10.29.1.2.5. As shown in Figure 10-224, each ranging round may be composed of an RCP, an RP, and an MRP, where each of these phases may consist of multiple slots.

In practice, it may be possible to merge some phases. For example, RCP and RIP may be merged into a single phase when the controller and the initiator are the same device. The MRP may be used to convey ranging-related service information via dedicated IEs.

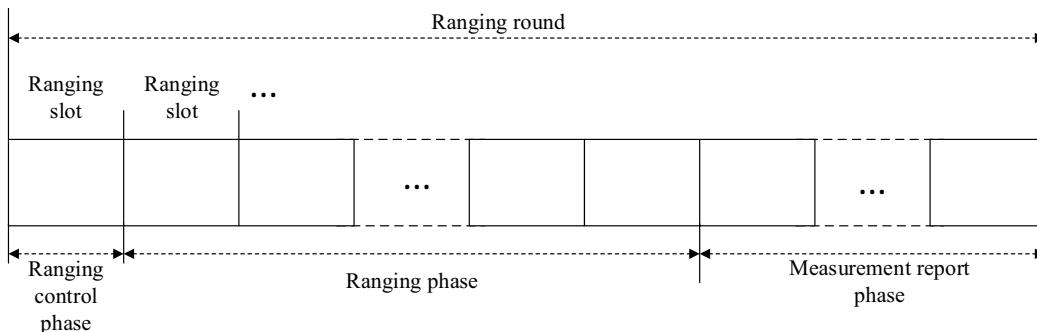


Figure 10-224—An example of phases in a ranging round

When the Schedule Mode field in the ARC IE is zero, it indicates that contention-based ranging is used. The first ranging slot index and the last ranging slot index for the ranging phase and/or measurement report phase are specified in the RCPS IE (described in 10.32.9.5). The RCPS IE provides the slot indices for the different phases in the ranging round. Where ranging phases for different ranging roles are not specified by the RCPS IE, the ERDEVs may contend for the remaining slots of the ranging round. When the Schedule Mode field in the ARC IE is one, it indicates that time-scheduled ranging is used. In this case, the slot allocation can be specified using the RDM IE (described in 10.32.9.8), or by an out-of-band mechanism.

In Figure 10-225, message ordering diagrams for different example cases of ranging procedures are presented. In each case, the RCM can be used to indicate the type of ranging that is used.

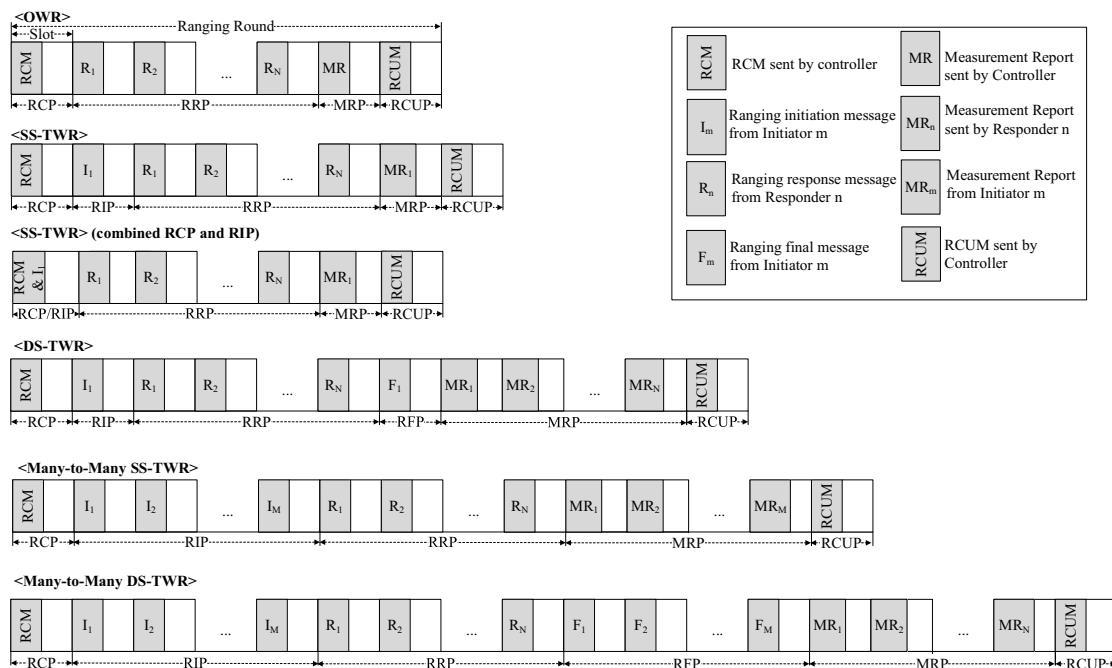


Figure 10-225—Example timing diagrams for some different multi-device ranging use cases

For ranging with the SP3 format packets, described in 16.2, in addition to the RCP and the RP, the controller may request certain information (e.g., AOA, reply time, or round-trip time measurements) from the controles participating in the ranging exchange. The controller may send its request in-band as part of the RCM, for example using the SP3 Ranging Request Reports IE (SRRR IE) described in 10.32.9.9, or this may be coordinated through some out-of-band mechanism.

Only time-scheduled ranging shall be used for SP3 ranging in order to differentiate messages from different devices. However, the scheduling can be static or dynamic via the RDM IE (described in 10.32.9.8). The scheduling can also be done via an out-of-band mechanism.

SP3 ranging may be performed without a measurement report phase in the ranging round (e.g., an ERDEV can use AOA from multiple ERDEVs to determine location).

One-to-many multi-node ranging with fixed reply times can be supported in the ranging block structure as shown in the example in Figure 10-226. All packets from the controller and the initiator will follow the slot structure. The i th responder will respond at fixed reply time FRT_i as shown in Figure 10-226, where i is from one to N responders. The fixed reply time FRT_j is measured from the RMARKER of the ranging initiation message $P1$ to the RMARKER of the response message, R_j . Furthermore, the following conditions should be satisfied such that the response frames fit into the allocated slots without overlap:

- $FRT_i > FRT_j$ for $i > j$.
- The time between consecutive ranging transmissions minus the packet length is $\geq K \times RSTU$, where K is a multiplier parameter that depends on the processing capabilities of the ERDEV receiver and chosen by the higher layers at ranging exchange setup.
- $FRT_N + \text{Packet length} < (N + 1) \times \text{Slot length}$.

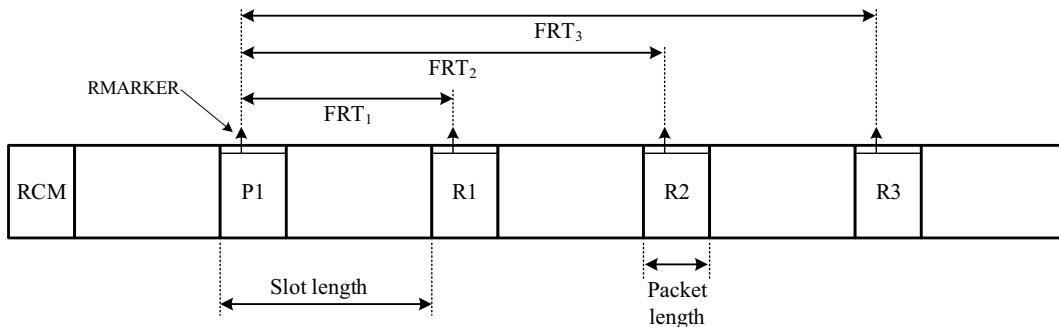


Figure 10-226—Example ranging round with fixed reply time

The requested fixed reply times can be exchanged via the RRTN IE (described in 10.29.8.6) before the ranging starts or via an out-of-band mechanism.

10.32.3 Ranging modes

10.32.3.1 Overview

Two different ranging modes are defined: interval-based mode and block-based mode.

The key difference between block-based mode and interval-based mode is that the mean time between successive ranging rounds in block-based mode is assumed to be constant (i.e., using a time structure with

uniform spacing), while interval-based mode adopts a time structure with adaptive spacing, and the time between successive ranging rounds may vary dynamically. The next higher layer of the controller selects the mode and the corresponding time structure. This selection may be achieved by an out-of-band mechanism or in-band using the Time Structure Indicator in the ARC IE as described in 10.32.9.1.

10.32.3.2 Interval-based mode

Interval-based mode utilizes the three intervals: block interval, round interval, and RIUM interval. Settings of these intervals are specified in the Ranging Interval Update IE (RIU IE) described in 10.32.9.2.

The following nomenclature is used in this mode:

- Ranging round set: A set of ranging round(s) covered by a specific RCM in a ranging block. Within a ranging round set, ranging rounds are contiguous (i.e., for consecutive ranging rounds, the first ranging slot of the second ranging round immediately follows the last ranging slot of the first ranging round).
- Block interval: Time remaining until the start time of the next ranging block relative to the start time of the current message.
- Round interval: Time remaining until the start time of the ranging round set relative to the start time of the ranging block.
- RIUM interval: Time remaining until the start time of the next RIUM relative to the start time of the current message.

In the first ranging round of a ranging round set, an RCM with the ARC IE (described in 10.32.9.1) configures ranging parameters of the ranging round set. The number of ranging rounds in the ranging round set is specified by the RCM Validity Rounds field of the ARC IE. A ranging block can consist of multiple ranging round sets, while each ranging round set is defined by its RCM at the beginning of the first ranging round of the set.

The controller transmits interval information to conteree(s) using an RIU IE described in 10.32.9.2. The RIU IE can be included in the RCM, RCUM, and RIUM. Upon reception of the RIU IE, each conteree knows the start time of next scheduled ranging round set. The controller can adjust block interval and round interval as a strategy to help reduce interference. The decision criteria and mechanism for adjusting block interval and round interval are out of scope of the standard.

A conteree can request a change to the current ranging configuration by sending a change request with the RCR IE (described in 10.32.9.7), to the controller. The RCR IE can be transmitted along with various IEs to indicate the preferred parameter settings of a conteree, such as the ARC IE (described in 10.32.9.1), the RIU IE (described in 10.32.9.2), the RCPSC IE (described in 10.29.8.5), and the RSSD IE (described in 10.29.8.2). The controller can receive the change request with the preferred ranging parameters in the ARC IE and the preferred intervals in the RIU IE from the conteree. After receiving the change request, the controller should decide whether to accept the change request or not. The controller can transmit an RCUM including IEs with updated ranging parameters. For example, the RCUM can include an RIU IE with updated intervals, which specify the start time of the next ranging block and the ranging round set.

The controller can transmit multiple RIUMs between ranging blocks as shown in Figure 10-227, each of which contains an RIU IE to indicate the block interval and next round interval values. The Remaining Number of RIUMs field in the RIU IE is decreased in each RIUM sent until it reaches zero, indicating that no more RIUMs should be expected in this ranging block.

Figure 10-227 shows a time diagram example of interval-based mode with one ranging round per ranging block.

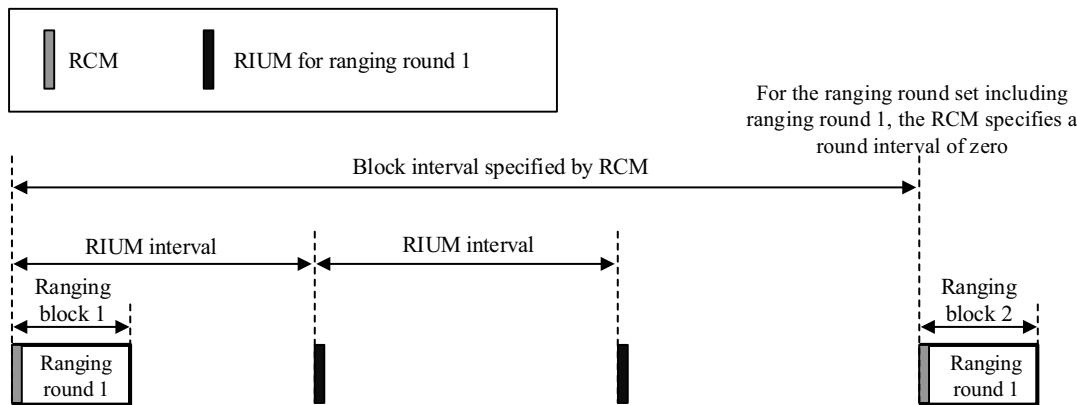


Figure 10-227—Time diagram for an example of interval-based mode with one ranging round per ranging block

In ranging round one of the first ranging block, the controller transmits an RCM that includes an ARC IE and RIU IE. The ARC IE content (as described in 10.32.9.1) is supplied to the next higher layer of the contreee to set its ranging parameters. Since the RCM covers one ranging round, the RCM Validity Rounds field in the ARC IE is set to one. The various block and round interval values are specified by corresponding fields in the RIU IE. Since the start time of the ranging block and the start time of the RCM are the same, the round interval for ranging round one of the second ranging block is zero. The Next Round Interval field in the RIU IE is zero to specify the round interval for ranging round one of the second ranging block. The controller can transmit RIUMs between ranging blocks. The Block Interval field, the RIUM Interval field, and the Remaining Number of RIUM field are updated in every RIUM.

Figure 10-228 shows a time diagram for an example of interval-based mode with two ranging rounds per ranging block.

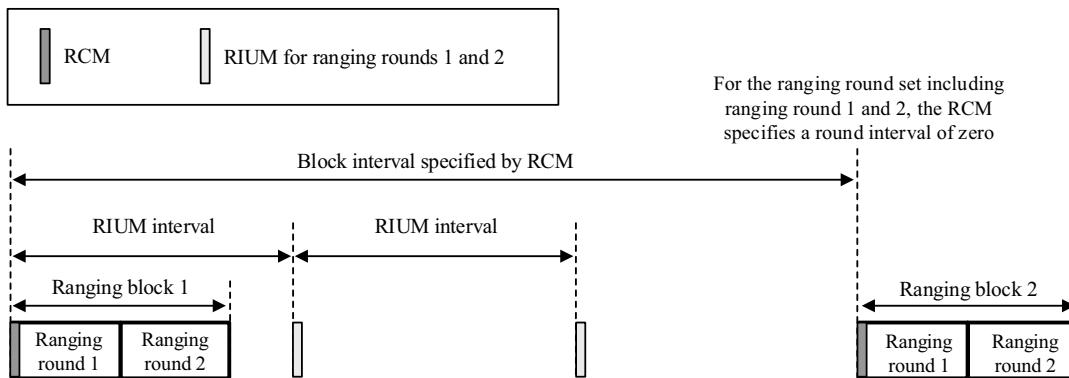


Figure 10-228—Time diagram for an example of interval-based mode with two ranging rounds per ranging block

In ranging round one of the first ranging block, the controller transmits an RCM that includes an ARC IE (as described in 10.32.9.1) and an RIU IE for ranging rounds one and two. Upon reception of the RCM, the contreees acquire the ranging parameters specified in the ARC IE. Since the RCM covers two ranging

rounds, the RCM Validity Rounds field in the ARC IE is two. The various block and round interval values are specified by the corresponding fields in the RIU IE. Since the start times of the subsequent ranging block and the RCM are the same, the round interval for the ranging round set of the second ranging block is zero. The Next Round Interval field in the RIU IE is zero to specify the round interval for the ranging round set of the second ranging block. The controller can transmit RIUMs between ranging blocks. The Block Interval field, RIUM Interval field, and Remaining Number of RIUM field are updated in every RIUM. The second ranging block has two ranging rounds for the same set of ERDEVs in the first ranging block.

Figure 10-229 shows a time diagram for an example of interval-based mode with two ranging round sets per ranging block.

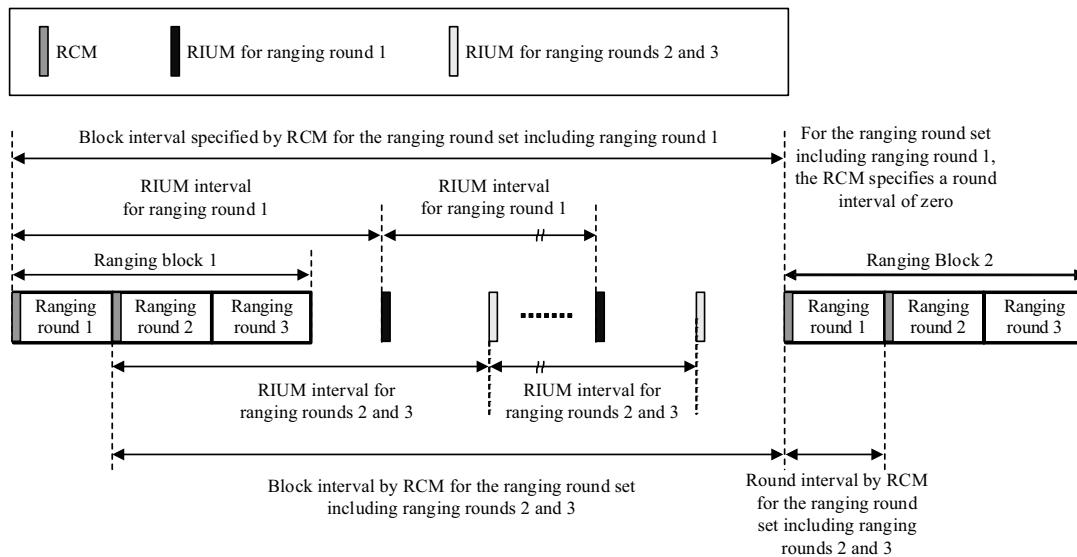


Figure 10-229—Time diagram for an example of interval-based mode with two ranging round sets per ranging block

The first ranging block has three ranging rounds. In ranging round one in the first ranging block, the controller transmits an RCM that includes the ARC IE (described in 10.32.9.1) and the RIU IE. Upon reception of the RCM, the continees acquire the ranging parameters specified in the ARC IE. The RCM Validity Rounds field in the ARC IE of the first RCM is one, which indicates that the first RCM covers one ranging round, that is ranging round one. The intervals are specified by the corresponding fields in the RIU IE. Since the start times of the next ranging block and the next RCM for ranging round one are the same, the round interval for ranging round one of the second ranging block is zero. Each RIUM for ranging round one is transmitted with the RIU IE, which specifies the intervals for ranging round one of the second ranging block. Since the second RCM covers two ranging rounds, that is ranging rounds two and three, the RCM Validity Rounds field in the ARC IE of the second RCM is two. Since the start times of the next ranging block and the next RCM for the second ranging round set including ranging rounds two and three are not the same, the round interval for the second ranging round set of the second ranging block is non-zero.

For different ranging round sets in a ranging block, the controller should have the same setting for the Ranging Block Duration field in the ARC IEs conveyed by different RCMs, while other ranging parameters and the participating ERDEVs can be different. For example, the ranging round sets with different ranging parameters can support different sets of ERDEVs with different capabilities, or the same set of ERDEVs for different applications.

If a conteree is not aware of the interval timings, it may recover by continuing to listen to the channel to receive a subsequent RCM.

If a conteree has information for the previous intervals updated by the previous RCM and fails to receive RCM, RCUM, or RIUM with updated intervals, the conteree will continue using the previous intervals.

When the controller updates intervals, it may use the previous intervals to transmit RIUMs including the RIU IE with the updated intervals to the conteree. If the conteree receives the RIUM, it can receive the RCM transmitted by the controller and send its RFRAFME in the ranging round with the updated intervals. The controller may stop transmitting the RIUM if the RFRAFME from the conteree is successfully received.

RCM Timing Window (RTW) operation is optionally specified by the RIU IE as described in 10.32.9.2. Specifically, a controller can send the RCM at random timing within a time window, namely RTW, centered at its originally scheduled time. The ranging parameters in the ARC IE and the intervals in the RIU IE need to be held constant across the ranging blocks when using RTW operation. The RTW size can be varied for subsequent ranging round sets. The RCM shall be transmitted within the RTW. In order to participate in the exchange, a conteree has to enable its receiver during the RTW in order to receive the RCM.

The controller and the conteree may change the size of the RTW by using the RTW Initial Size field or RTW Multiplier field of the RIU IE. The RTW shall not start before the previous ranging block ends. If the RTW configuration is conveyed by the RIU IE for the subsequent ranging round set, the controller randomly chooses the transmission timing of the next RCM within the RTW. The conteree waits during the RTW to receive the RCM.

Figure 10-230 shows a timing diagram for an example of the RCM transmission with the RTW. RCMs are transmitted at random time within the RTW.

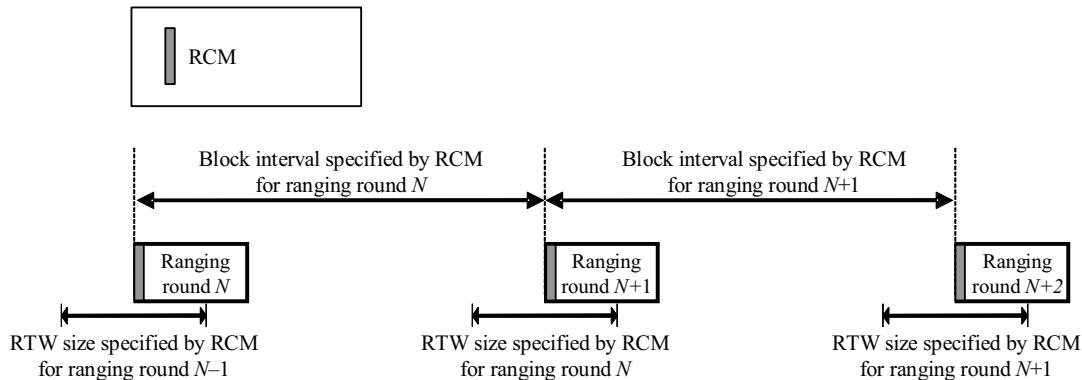


Figure 10-230—Time diagram for an example of RCM transmission with RTW

Since the ranging parameters in the ARC IE and the intervals in the RIU IE need to be held constant across the ranging blocks during RTW operation, the interval specified by the RCM of ranging round N and the interval specified by the RCM of ranging round $N + 1$ are the same. If a conteree fails to receive the RCM of ranging round $N + 1$, the conteree can receive the RCM of ranging round $N + 2$ transmitted at random time within the RTW of ranging round $N + 2$.

10.32.3.3 Block-based mode

Block-based mode uses a structured timeline where the ranging block structure, as defined in 10.32.2, is periodic by default. Figure 10-231 shows an example timing diagram for block-based mode. The ranging

block structure can be setup by specifying the Ranging Block Duration field, the Ranging Round Duration field, and the Ranging Slot Duration field in the ARC IE (as described in 10.32.9.1).

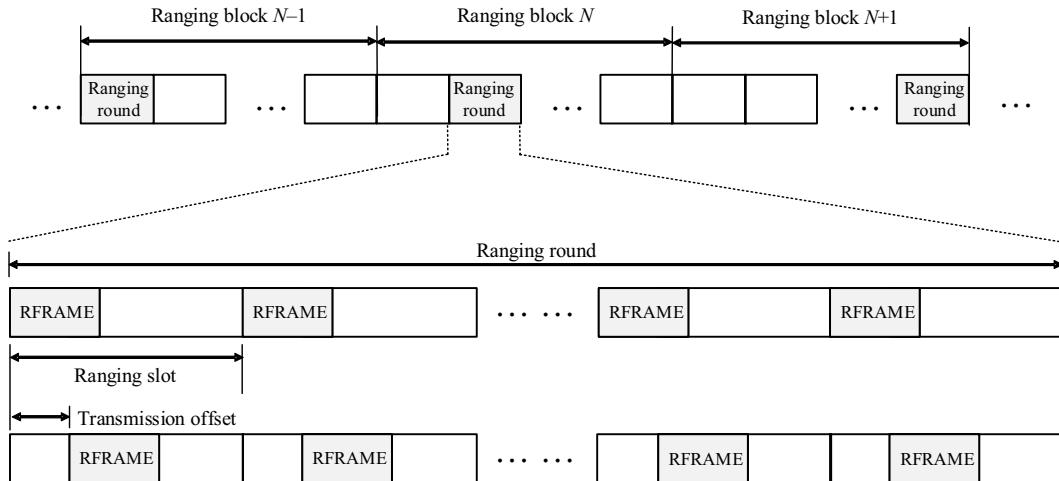


Figure 10-231—Time diagram for an example of block-based mode

The number of ranging rounds in a ranging block is derived by:

$$\text{Number of ranging rounds} = \frac{\text{Ranging block duration}}{\text{Ranging round duration}}$$

The number of ranging slots in a ranging round is then given by:

$$\text{Number of Ranging slots} = \frac{\text{Ranging round duration}}{\text{Ranging slot duration}}$$

These fields completely define the ranging block structure. An ERDEV that receives an RCM successfully may set the initial ranging block structure and the associated timeline for ranging using the values of those ARC IE fields. Alternatively, the ranging block structure may be setup and/or fixed by the next higher layer.

The ranging block structure can be repeatedly transmitted in every RCM by the controller. If the ranging block structure needs to be changed or updated (i.e., to a new ranging block duration, ranging round duration, and/or ranging slot duration), the controller may send a Ranging Block Update IE (RBU IE), as described in 10.32.9.4, to signal the new configuration. In addition to the new block structure configuration, the RBU IE also includes a Relative Ranging Block Index field indicating the number of remaining ranging blocks with the current configuration before switching to the new configuration. The RBU IE can be sent either in the RCM or in the final Data frame of a ranging message sequence. Each time the RBU IE is sent, the controller will reduce the Relative Ranging Block Index field by one until it reaches zero. This signals that the next block will be using the new configuration and that the RCM ARC IE in the next block will include the new configuration. Alternatively, the ranging block structure update is signaled to the participating ERDEVs via the next higher layer.

For a given block configuration, each ranging block is referenced by a ranging block index relative to the first block in that configuration (block number zero). Each ranging round in any ranging block is referenced by a ranging round index relative to the first ranging round in the current ranging block. For example, if the ranging block has M ranging rounds, the first ranging round in the block will have ranging round index zero

and the last ranging round in the block will have ranging round index $M - 1$. Similarly, each ranging slot in a ranging round is referenced by a ranging slot index relative to the first ranging slot in the ranging round. For example, in a ranging round with K ranging slots, the first ranging slot in the round will have ranging slot index of zero and the last ranging slot in the round will have ranging slot index $K - 1$. A new ranging message exchange will start by transmitting the first RCM in ranging slot zero of ranging round zero in ranging block zero.

The Ranging Round IE (RR IE), as defined in 10.32.9.3 can be used to signal the ranging round information regarding:

- The current ranging round (i.e., ranging round in the current ranging block i). In this case, the RR IE will be included in the RCM of ranging block i . The transmission of the RR IE in the RCM of the current ranging round will aid the ERDEV to synchronize to the block structure.
- The next ranging round (i.e., ranging round in the next ranging block $i + 1$). In this use case, if the last scheduled message in the current ranging round (of ranging block i) is a message sent by the controller to the controlees, the RR IE will be sent in this final message to signal ranging round information for ranging block $i + 1$. If the last scheduled message in the current ranging round (of ranging block i) is not from the controller but from a conteree, then the controller will send the RR IE in the RCM of the next ranging block (ranging block $i + 1$) to signal the ranging round information for ranging block $i + 2$. In this case, the RCM of ranging block $i + 1$ will have two instances of the RR IE. The first one is applicable to a ranging round in ranging block $i + 1$ and the second one is applicable to ranging block $i + 2$.

In the first ranging round of a ranging message exchange, the RCM packet is transmitted at the beginning of the ranging slot. This RCM will include an RR IE to signal information regarding the ranging round in the current ranging block. In subsequent ranging rounds, the controller may decide to start the transmission within each slot at a different transmission offset. This will be signaled by the controller in the Transmission Offset field of a second instance of the RR IE. This offset should be less than the ranging slot duration minus the UWB packet duration. Figure 10-232 shows an example of ranging rounds with different transmission offsets.

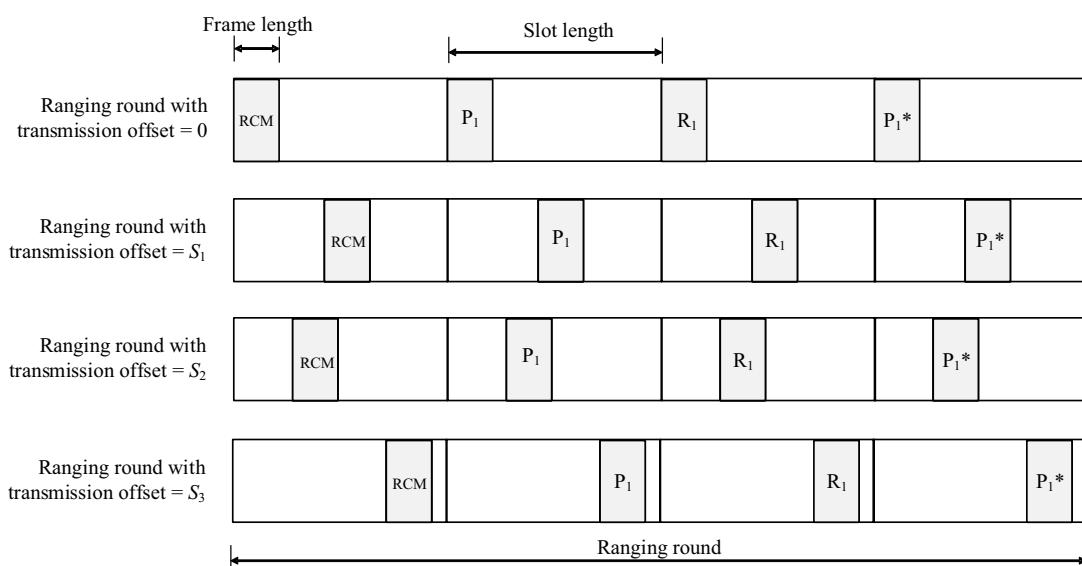


Figure 10-232—Ranging rounds with different transmission offset

The transmission offset is expressed as a multiple of RSTU. All packet transmissions within the same ranging round should be transmitted with the same transmission offset. The next higher layer of the controller is responsible for choosing the transmission offset and communicating it to all other devices in the RR IE. The controller may change the transmission offset of each ranging round as a strategy to help reduce interference. Controlees should send at the specified offset in their slots, otherwise the packets may be missed by receiving devices expecting the transmission at that offset.

Additionally, participating ERDEVs may continue to use the same ranging round in the next ranging block (i.e., if they are using ranging round m in ranging block n , they will also use ranging round m in ranging block $n + 1$). Alternatively, the controller may decide to “hop” to a different ranging round in the next ranging block (i.e., if participating ERDEVs are using ranging round m in ranging block n , they will use ranging round k in ranging block $n + 1$, where $k \neq m$). Figure 10-233 shows an illustration of the concepts of transmission offset and round hopping. The criteria used to determine when to change the transmission offset and/or hop to a different relative ranging round is outside the scope of the standard and is assumed to be a next higher layer function/protocol. However, it is assumed that as part of such function/protocol, the devices participating in the ranging exchange have either (a) pre-negotiated a hopping sequence that is known to all devices, or (b) have exchanged all the information necessary such that each device can generate the hopping sequence so that they know which ranging round in each ranging block is to be used if hopping is triggered. If the ranging block structure is updated (by sending an RBU IE or by a next higher layer protocol), the participating ERDEVs can set the transmission offset to zero and reset the block, round, and slot indices at the beginning of the new ranging block structure.

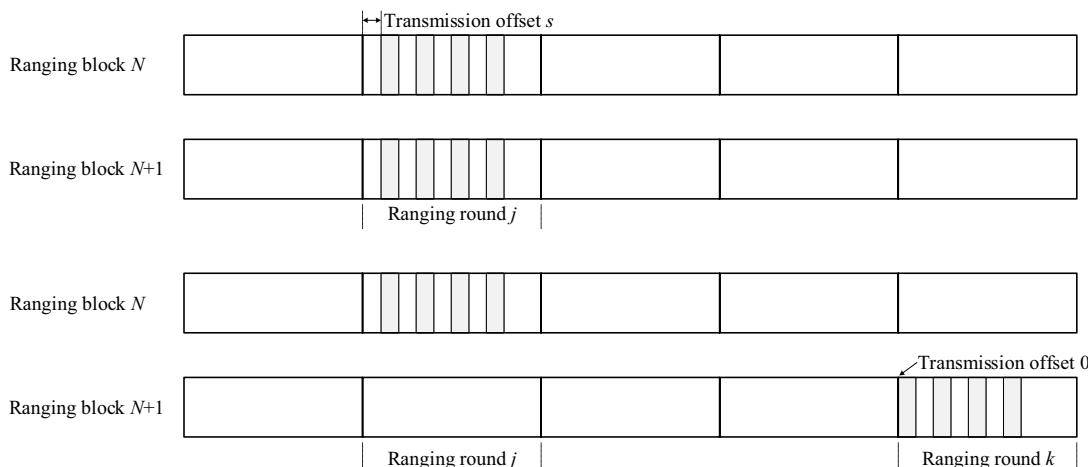


Figure 10-233—Illustration of transmission offset and round hopping

In the allocated ranging round of a ranging block, the controller configures the ranging round by sending the RCM with the ARC IE (described in 10.32.9.1) and the RR IE (described as defined in 10.32.9.3). The controller next higher layer is responsible for selecting the hopping mode and transmission offset to be used in the ranging round of the next ranging block. If the last scheduled message in the current ranging round in block i is a message sent by the controller to the controlees, then the controller will send the RR IE in this last message of the current ranging round to signal to the participating ERDEVs whether to hop to a different round and/or use a different transmission offset in the ranging round of the next ranging block $i + 1$. If the last scheduled message in the current ranging round is not from the controller, then the controller will send a second RR IE in the RCM of the ranging round in block $i + 1$ to signal to the participating ERDEVs whether to hop to a different round and/or use a different transmission offset in the ranging round of ranging block $i + 2$. Note that in this last case, the RCM in block $i + 1$ will include two instances of the RR IE. The first instance is applicable to ranging in block $i + 1$ while the second instance is applicable to ranging in block $i + 2$. The contents of the RR IE will be the Ranging Block Index field and Ranging Round Index field of the

current ranging block, the Hopping Mode field and the Transmission Offset field for the ranging round of the next ranging block. After receiving the RR IE in the final message of a ranging message sequence or as a second RR IE instance in an RCM, the conteree next higher layer is responsible for using the indicated ranging round and transmission offset in the subsequent ranging block. If the conteree does not receive the RR IE (either in the final message of the exchange or in the RCM), for example due to an interference event, the conteree can turn on hopping in the next ranging block and move to a new ranging round (as determined by the new hopping mode, next ranging block index, and hopping sequence) with a transmission offset of zero. An ERDEV that misses the ARC IE but correctly receives the RR IE in the last message in the current round can use the content of the RR IE to resynchronize to the block structure and be able to receive the RCM and ARC IE in the next ranging block so long as the ranging block structure is unchanged. The ranging block structure, specified by the ARC IE and RR IE sent in the RCM, as well as the RR IE and RBU IE sent either in the last message or in the RCM, allows each participating ERDEV to maintain synchronization with the ranging block structure while being idle with its receiver turned off during unused slots to save energy.

10.32.3.4 Receiver enable in slotted ranging schemes

In multi-device slotted ranging schemes rather than leaving the receiver on all the time, the next higher layer can use the MLME-RX-ENABLE.request to enable reception just in the slots where messages are expected to be received. The MCPS-DATA.indication and MLME-RX-ENABLE.indication can be used by the next higher layer to keep track of which slots it receives packets in and which it does not. This is illustrated in Figure 10-234.

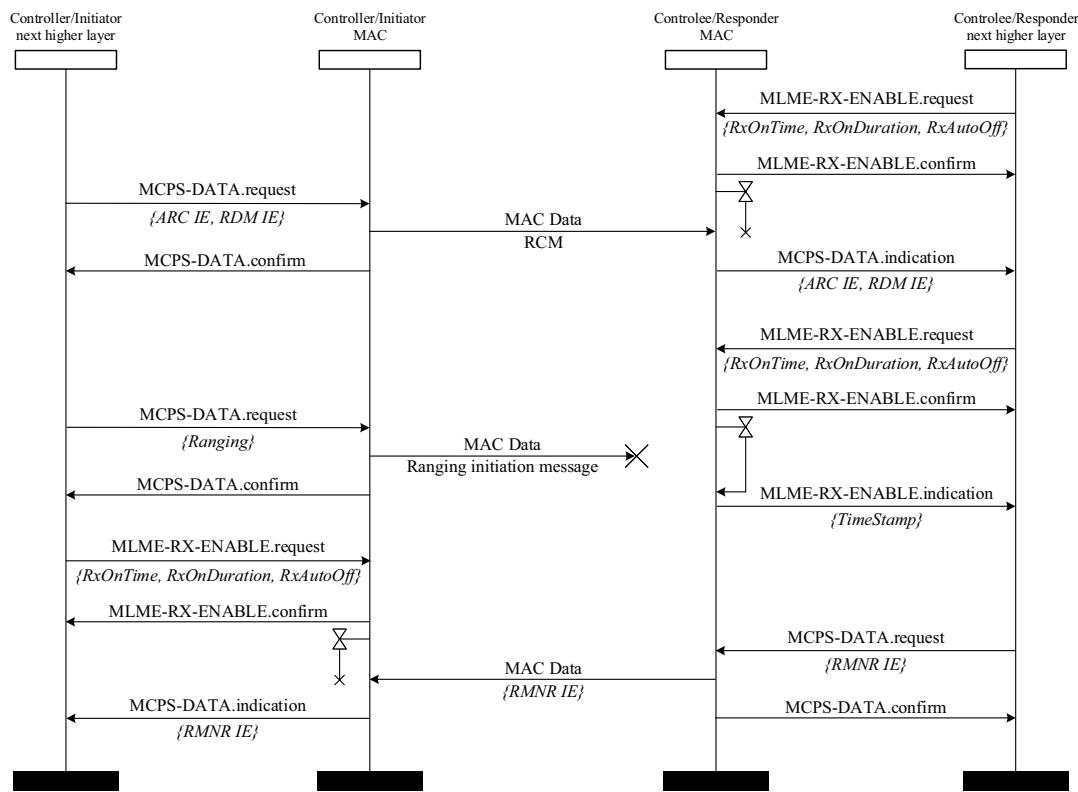


Figure 10-234—Message sequence chart illustrating MLME-RX-ENABLE.indication use

10.32.4 Ranging procedure for one-to-many SS-TWR

For one-to-many SS-TWR, as shown Figure 10-235, the example ranging exchange is started by the initiator, where the RRMC IE as described in 10.29.8.3 is embedded in the ranging initiation message broadcast to multiple responders.

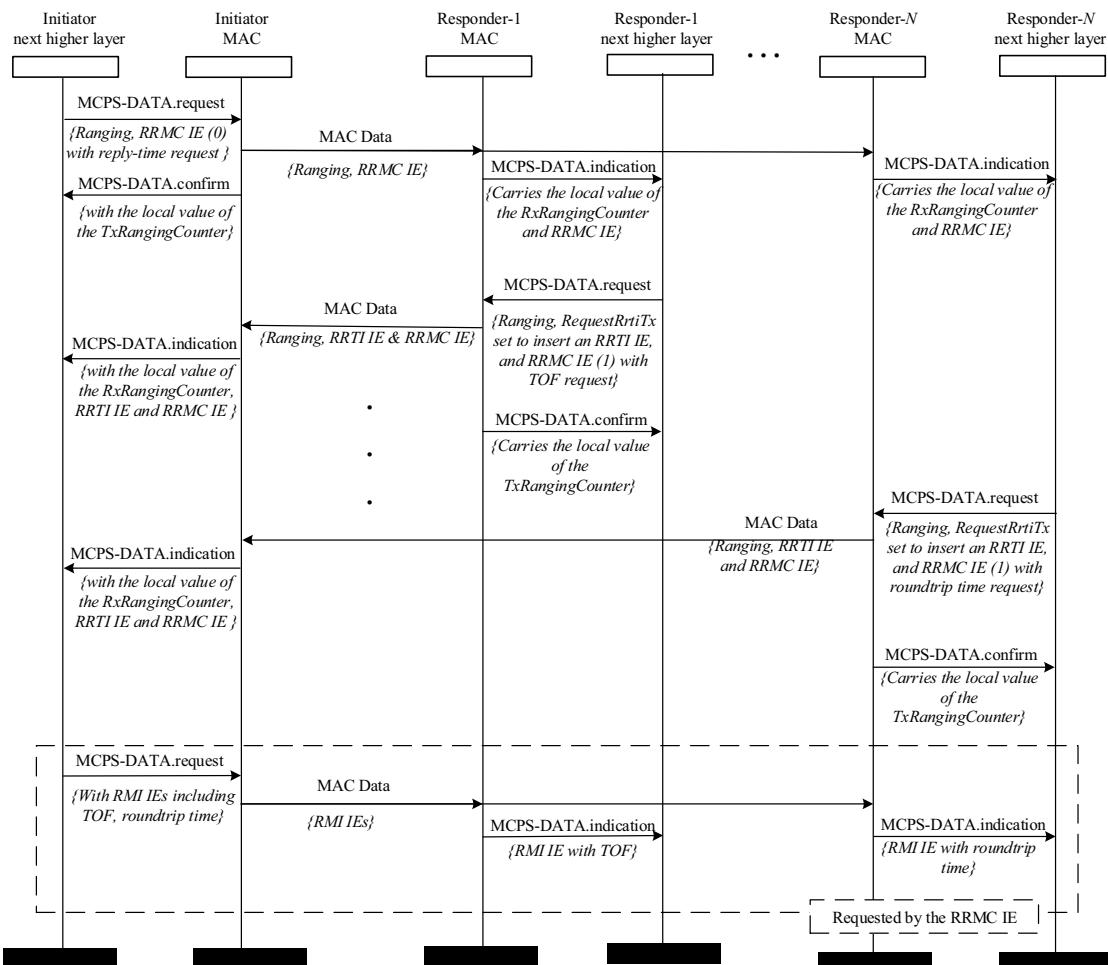


Figure 10-235—Message sequence chart for one-to-many SS-TWR

The Ranging Control Information field of the RRMC IE is set to zero according to Table 10-151, indicated by the designation RRMC IE (0) in Figure 10-235. The Reply Time Request field of the RRMC IE is set to one, to request the reply time from the responding ERDEV. At the responder side, the RRMC IE delivered by the MCPS-DATA.indication primitive signals to the next higher layer that it should initiate a ranging response. The MCPS-DATA.request primitive is issued by each responder with the RequestRtiTxList parameter set to insert the RRTI IE (described in 10.29.8.1) and to convey the RRMC IE with Ranging Control Information field set to one (as per Table 10-151) and indicated by the designation RRMC IE (1) in Figure 10-235. The response RFRAIMEs are unicast to the initiator.

For the multi-node ranging based on scheduling (as described in 10.32.2), responders send response messages in their assigned time slots, while for multi-node ranging based on the contention, responders contend in the time slots in the ranging response phase.

Figure 10-235 illustrates the message sequence chart for one-to-many SS-TWR between one initiator and N responders, that is Responder-1, Responder-2, ..., Responder- N , where ranging response messages from different responders are scheduled for transmission in sequence. Upon receiving each ranging response frame, the initiator has sufficient information to calculate the TOF to that responder. Different responders can have different requests of ranging results. In Figure 10-235, for example, Responder- N requests the TX-to-RX round-trip time, that is the Round-trip Time Request field value of the RRMC IE in the ranging response message is set to one, while Responder-1 requests the ranging result, that is the TOF Request field value of the RRMC IE in its ranging response message is set to one. The final message broadcast by the initiator conveys one or more RMI IE(s) (described in 10.29.8.4) to fulfill the measurement reports, where the Address field of the RMI IE distinguishes to which node the reported measurements relate. If multiple responders request the same set of information, for example TOF, that measurement report can be fulfilled by one RMI IE in the final data message.

10.32.5 Ranging procedure for one-to-many DS-TWR

For one-to-many DS-TWR, the three-message ranging method can be used in order to reduce the number of transmissions. The ranging exchange is started by the initiator broadcasting a ranging initiation message with an embedded RRMC IE (as described in 10.29.8.3) selecting the responders and with its Ranging Control Information field set to two (as per Table 10-151) as indicated by the designation RRMC IE (2) in Figure 10-236.

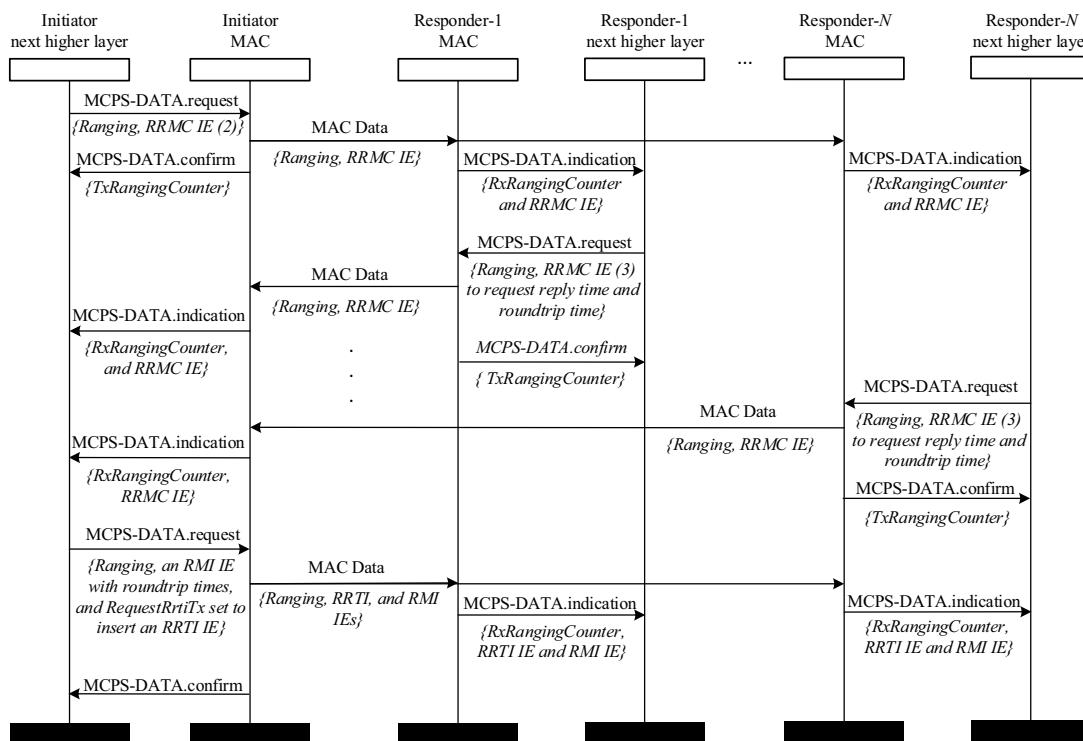


Figure 10-236—Message sequence chart for one-to-many DS-TWR: no request of ranging result from the initiator

Each responder receiving the ranging initiation message will respond in sequence with a ranging response message that serves to end the first round-trip measurement and initiate the second round-trip time measurement. Each such response message contains an RRMC IE, (indicated by the designation RRMC IE (3) in Figure 10-236), with the Ranging Control Information field set to three (as per Table 10-151), and with its Reply Time Request field and Round-trip Time Request field set to request the first round-trip time

and the reply time of the final RFRAME from the initiator. Similar to one-to-many SS-TWR (in 10.32.4), ranging response messages of different responders can be scheduled, or contend for the time slots in the ranging response phase.

To complete the ranging measurement, the initiator broadcasts the final RFRAME to convey to the different responders an RMI IE (described in 10.29.8.4) to report the round-trip times, and an RRTI IE (described in 10.29.8.1) to report the reply times.

Figure 10-236 illustrates the message sequence chart for multi-node DS-TWR between one initiator and N responders, that is Responder-1, Responder-2, ..., Responder- N , where response frames from different responders are scheduled for transmission in a sequential order. Upon receiving the second MCPS-DATA.indication primitive each responder has sufficient information to calculate its TOF to the initiator. In Figure 10-236, the responders do not send measurements back to the initiator, which would be the case if the Reply Time Request field, Round-trip Time Request field and TOF Request field are all zero in the RRMC IE sent by the initiator.

Figure 10-237 illustrates the message sequence chart for one-to-many DS-TWR when the Deferred Mode field is one in the ARC IE (described in 10.32.9.1). Therefore, the initiator sends the first round time and second reply time to the responders using RMI IEs (described in 10.29.8.4) in a deferred Data frame (with the Deferred Mode field of the RMI IE set to one).

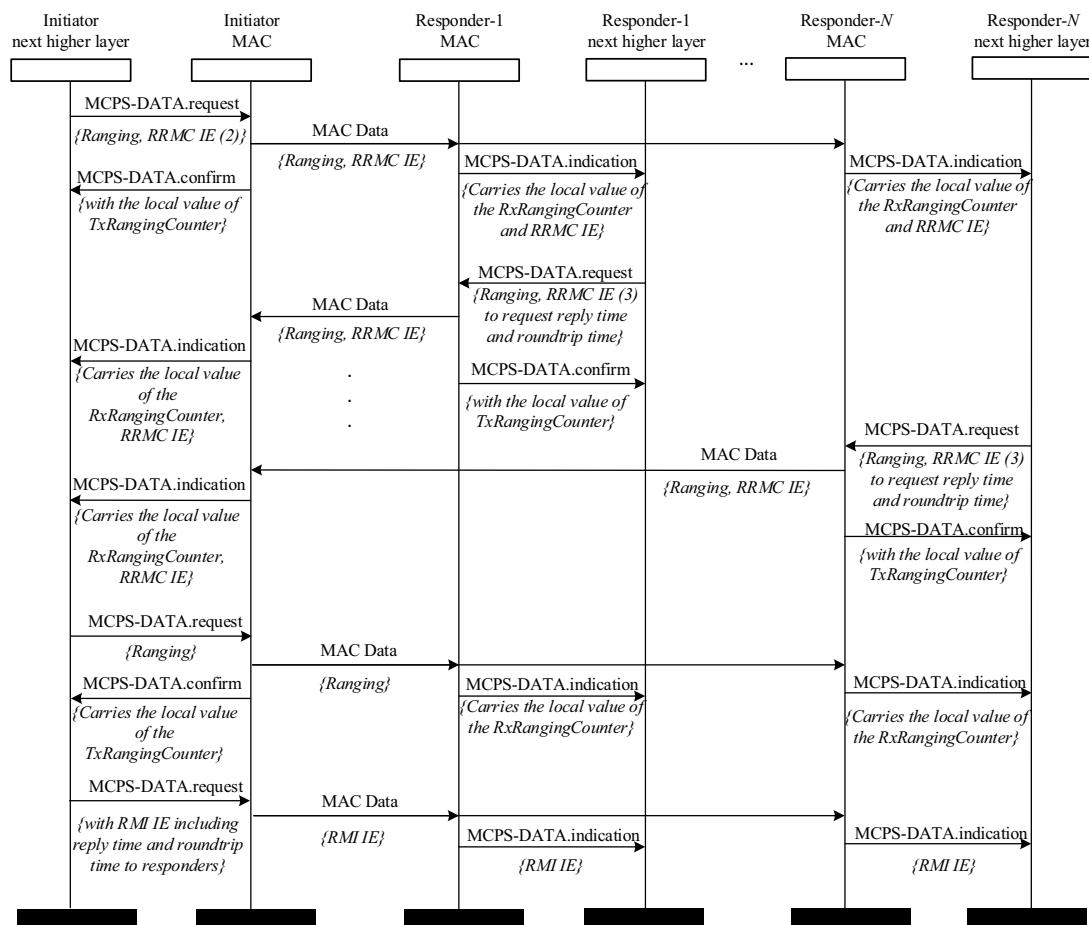


Figure 10-237—Message sequence chart for one-to-many DS-TWR: no request of ranging result from the initiator with deferred mode

In Figure 10-238, the initiator requests the first reply time and second round-trip time at the responder by setting the Reply Time Request field and Round-trip Time Request field in the RRMC IE of the ranging initiation message. Upon reception of this RRMC IE (2), the responder's next higher layer initiates the second round-trip time measurement with RRMC IE (3), and using the RequestRrtiTxAList parameter of the MCPS-DATA.request primitive causes the MAC to insert RRTI IE(s) in the response RFRAME. When sending the final RFRAME, the next high layer of the initiator sets the RequestRrtiTxAList parameter of the MCPS-DATA.request primitive to insert an RRTI IE for each responder, and also conveys the RMI IE reporting the first round-trip time measurements. Since the initiator requests the second round-trip time from the responder, a separate Data frame is transmitted by each responder to send this information, allowing the initiator to also be able to calculate the TOF after the measurement report phase.

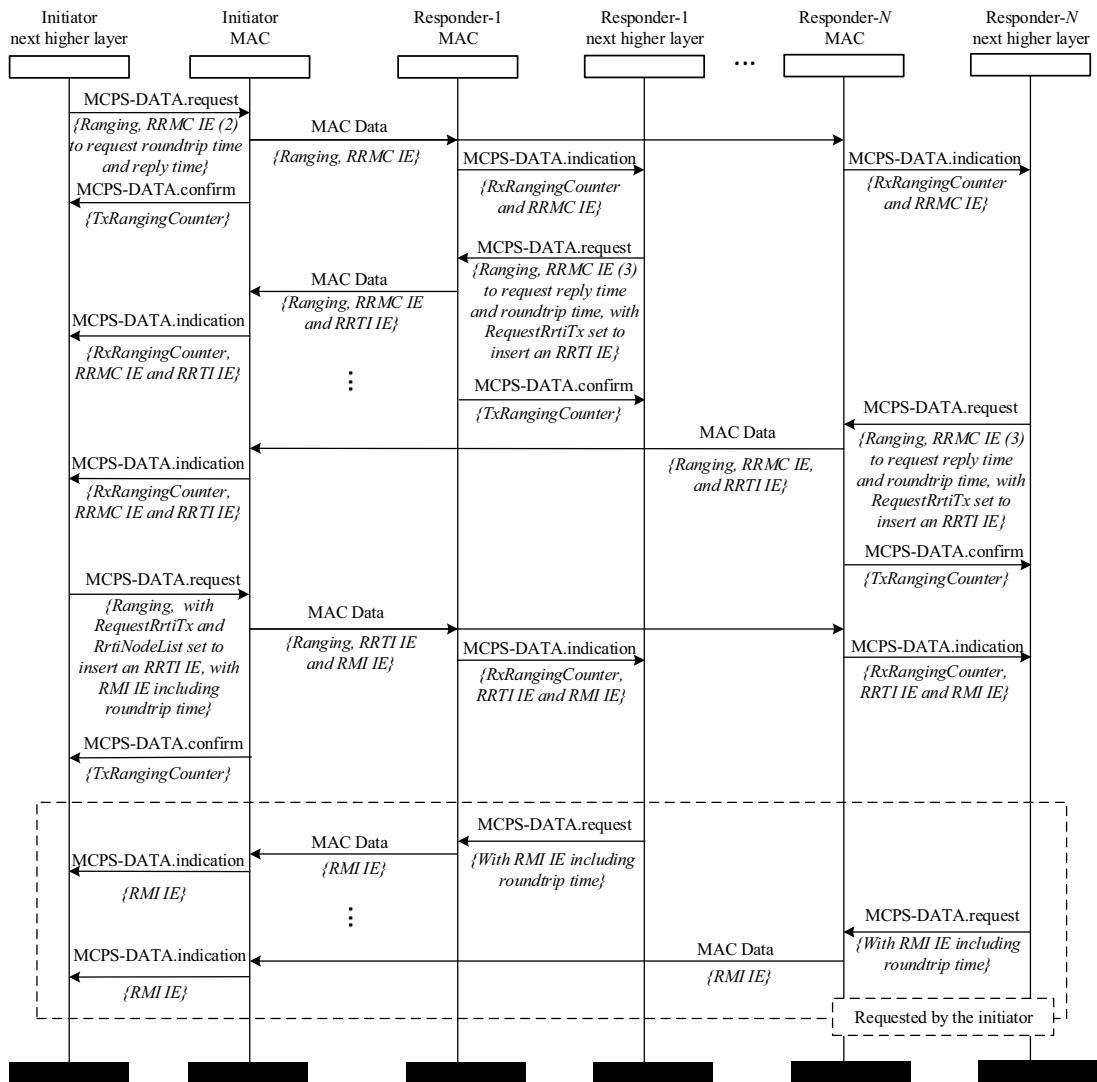


Figure 10-238—Message sequence chart for one-to-many DS-TWR: request of the first reply time and second round-trip time from the initiator

In Figure 10-239, the initiator requests the ranging result, that is the TOF, by setting the TOF Request field to one in the RRMC IE of the ranging initiation message. Therefore, the responders respectively send back the ranging result (RMI IE) in separate Data frames based on either time-scheduling or contention.

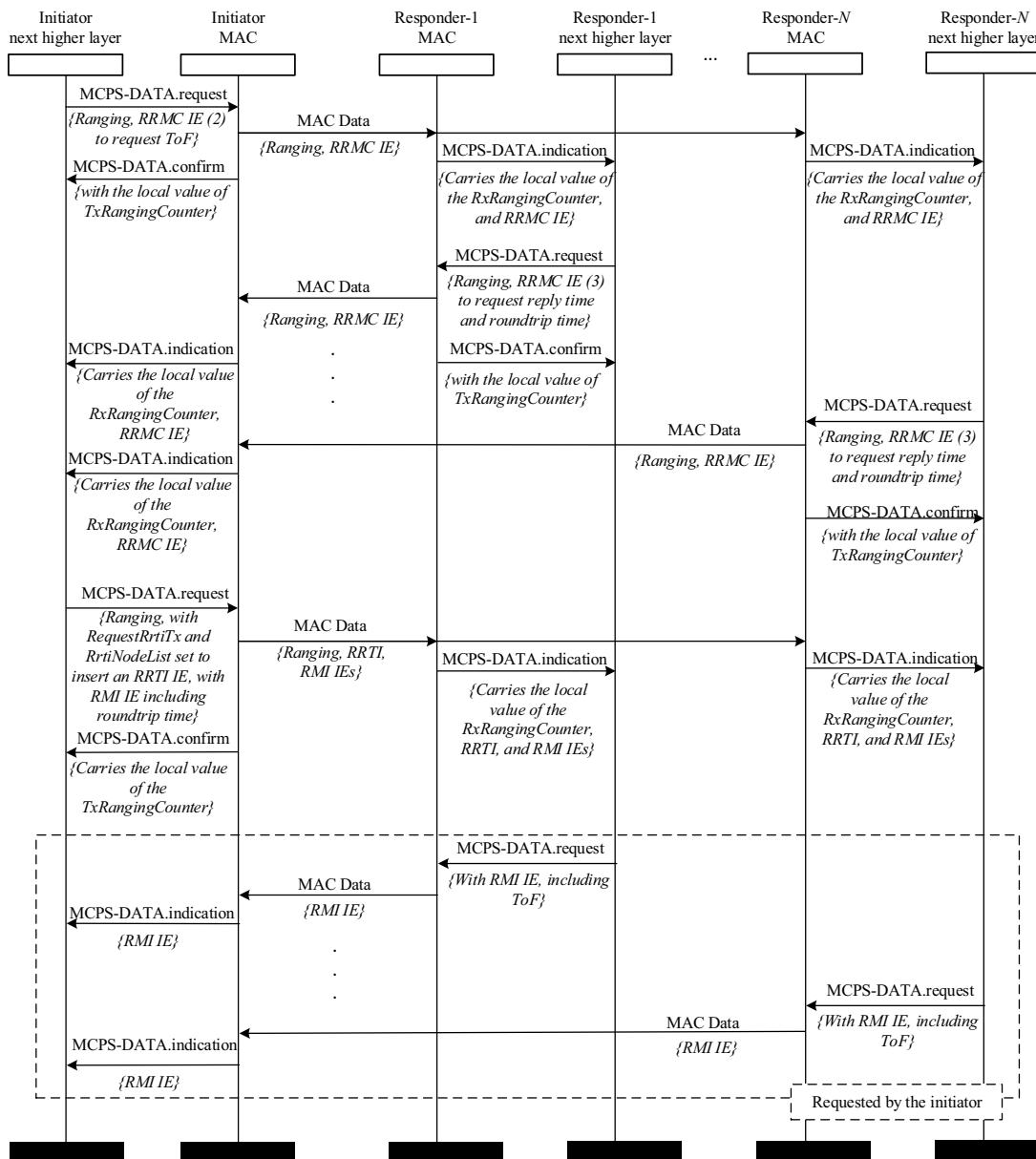


Figure 10-239—Message sequence chart for one-to-many DS-TWR: request of ranging result from the initiator

10.32.6 Ranging procedure for many-to-many SS-TWR

For the scenario of many-initiators-to-many-responders (M2M), the controller sends the RCM with the ranging configuration to multiple initiators and responders. In the scenario of one-to-many ranging, there is only one ranging initiation message in the ranging initiation phase (RIP) from a single initiator, while in this many-to-many case, multiple initiators can send the ranging initiation messages in the RIP through either scheduling or contention in M2M ranging. The ranging initiation message contains an RRMC IE (as

described in 10.29.8.3), with the Ranging Control Information field set to zero and Reply Time Request field set to one. After collecting ranging initiation messages from different initiators, the next higher layer of each responder initiates the response RFRAFME using the MCPS-DATA.request primitive with the RequestRrtiTxDList parameter set to insert an RRTI IE (described in 10.29.8.1) for each initiator. The response RFRAFMEs are sent to the initiators in the ranging response phase based on time-scheduling or contention determined via the ranging configuration.

Figure 10-240 illustrates the message sequence chart for M2M SS-TWR between M initiators and N responders, that is Initiator-1, Initiator-2, ..., Initiator- M , and Responder-1, Responder-2, ..., Responder- N , where transmission of both ranging initiation and ranging response messages are scheduled in a sequential order. Contention-based transmissions for both ranging initiation phase and ranging response phase can also be implemented. Upon receipt of each MCPS-DATA.indication primitive delivering a ranging response message, each initiator next higher layer has sufficient information to calculate its TOF to that responder. It is the responsibility of the higher layers to provide each required response in good time to allow the MAC to transmit it at the specified time, and similarly to have enabled the receiver in good time to receive any message it needs to receive. The controller can ascertain this using the ARC IE (described in 10.32.9.1) and RDM IE (described in 10.32.9.8). In Figure 10-240, the responders do not request the ranging results. However, as in Figure 10-235, the responders can request ranging results from the initiators, which would require an additional Data frame to be transmitted by each initiator.

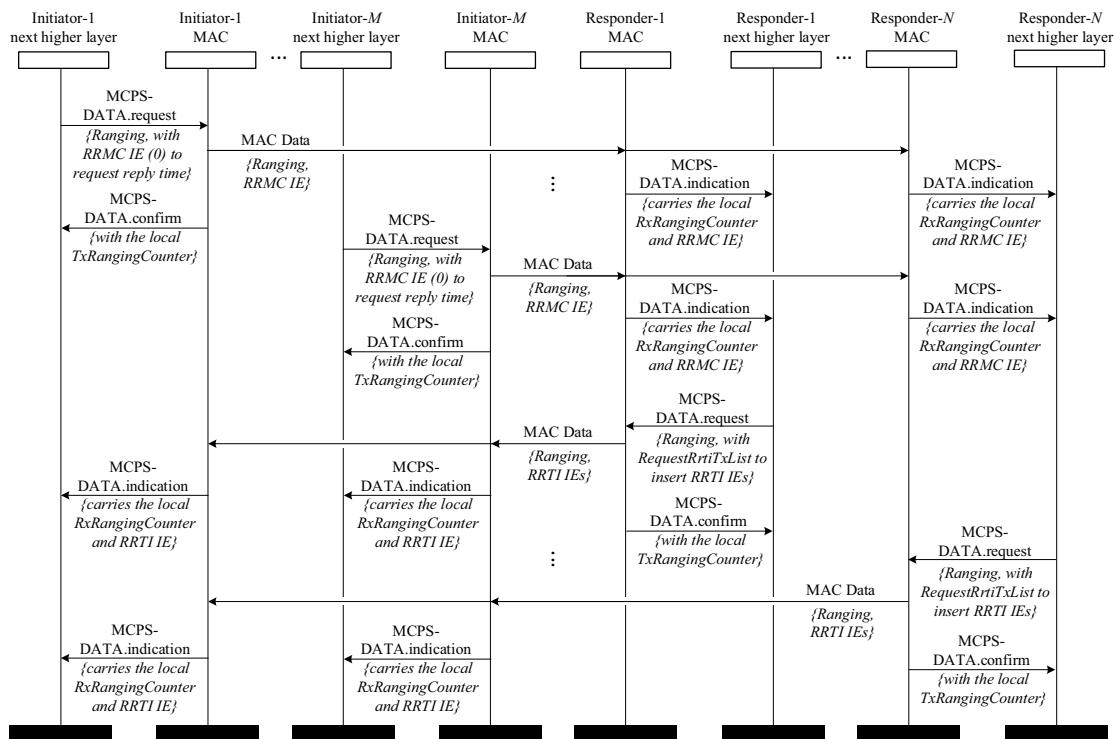


Figure 10-240—Message sequence chart for M2M SS-TWR

10.32.7 Ranging procedure for many-to-many DS-TWR

For M2M DS-TWR, based on the ranging configuration, multiple initiators will contend or be time-scheduled for the time slots in the ranging initiation phase to send the ranging initiation messages, which convey RRMC IEs (as described in 10.29.8.3). The Ranging Control Information field in the RRMC IE is set to two, which is indicated by the designation RRMC IE (2) in Figure 10-241.

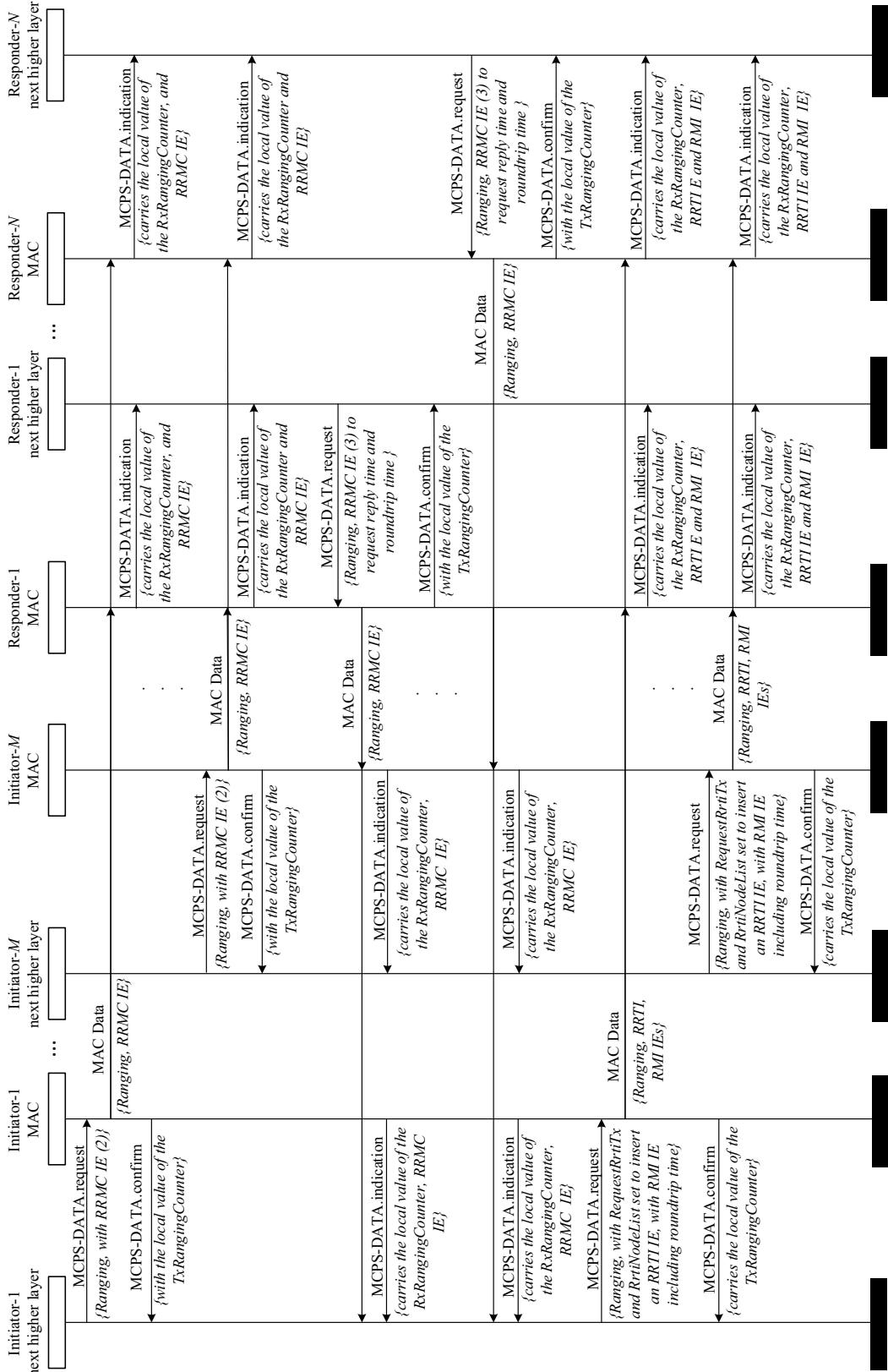


Figure 10-241—Message sequence chart for M2M DS-TWR

After the ranging initiation phase, each responder forms a response message, containing the RRMC IE to initiate the second round-trip time measurement, with the Ranging Control Information field set to three, designated RRMC IE (3) in Figure 10-241, and Reply Time Request and Round-trip Time Request fields both set to one. The ranging response messages can be transmitted through either time-scheduling or contention determined via ranging configuration. Then, each initiator forms a final RFRAFME, which includes an RRTI IE (as described in 10.29.8.1) to report the reply time, and an RMI IE (as described in 10.29.8.4) to report the round-trip time.

Figure 10-241 illustrates the message sequence chart for M2M DS-TWR between M initiators and N responders, where both ranging initiation messages and ranging response messages are scheduled for transmission in a sequential order. Upon receiving the second MCPS-DATA.indication primitive reporting the arrival of the final RFRAFME from an initiator, each responder's next higher layer has sufficient information to calculate its TOF to the initiator.

10.32.8 Ranging procedures with SP3 format packets

10.32.8.1 Introduction

In this subclause, the examples of SP3 packet based ranging procedures are illustrated by message sequence charts in Figure 10-242 and Figure 10-243, corresponding to multi-node SS-TWR and DS-TWR, respectively. Unicast ranging can be viewed as a subset of multi-node ranging. The procedures can be generalized to accommodate use cases with many initiators and many responders.

10.32.8.2 Ranging procedure for multi-node SS-TWR with SP3 packets

Figure 10-242 illustrates an example of one-to-many SS-TWR with SP3 ranging, which consists of three phases, corresponding to RCM, SP3 ranging, and data report, respectively, where “ R_i ” represents the i th responder and “ I ” represents the initiator. In this example, the first responder is the controller, while the other responders are controles. At the beginning of the ranging round, the RCM conveys the ranging configuration information, and request-related IEs. For example, “SRRR IE (I, R_1)” indicates that Responder-1 requests AOA and the round-trip time from the initiator side, where the RAOA field and RRTT field of the SRRR IE (described in 10.32.9.9) are both set to one.

Multi-node SP3 ranging is based on scheduling determined by the next higher layer of the controller, where each time slot is allocated to a particular ERDEV to use. The RDM IE (described in 10.32.9.8) in the RCM is used to convey the assignment of time slots and device roles in a ranging round. The ARC IE (described in 10.32.9.1) specifies the ranging procedure and the SP3 packet format, thus the ERDEV next higher layer is aware of the SP3 ranging phase start and end, and can invoke the MLME-STS primitive to enable (and disable) the SP3 packet configuration before (and after) the ranging phase. The RCM may convey the RSSD IE (described in 10.29.8.2) to exchange the parts of the STS seed to initialize the generation of STS among participating ERDEVs. According to the scheduling information of ranging transmissions, the value of the STS counter at the participating ERDEVs needs to be appropriately advanced and set for transmission and reception of the SP3 packets.

After the RCM, the SP3 ranging starts. The next higher layer is responsible for properly configuring the operation at both ends, which involves use of the MLME-STS.request primitive to select the SP3 packet format, and setting the *phyHrpUwbStsSeed*, *phyHrpUwbStsVUpper96*, and *phyHrpUwbStsVCounter* attributes to the correct values. Since ranging scheduling is specified by the RCM in advance of the SP3 ranging, the devices already know the identities of the participants. Figure 10-242 and Figure 10-243 are based on the time structure shown in Figure 10-224, where the ranging controller adds the SRRR IE (described in 10.32.9.9) to the RCM as required. In some specific applications, the need for reports can be known a priori by means of an out-of-band mechanism. The MAC sublayer of each device reports the arrival time of the received RFRAFME to its next higher layer via the MCPS-DATA.indication, so that this information can be used to calculate reply time or round-trip time measurement.

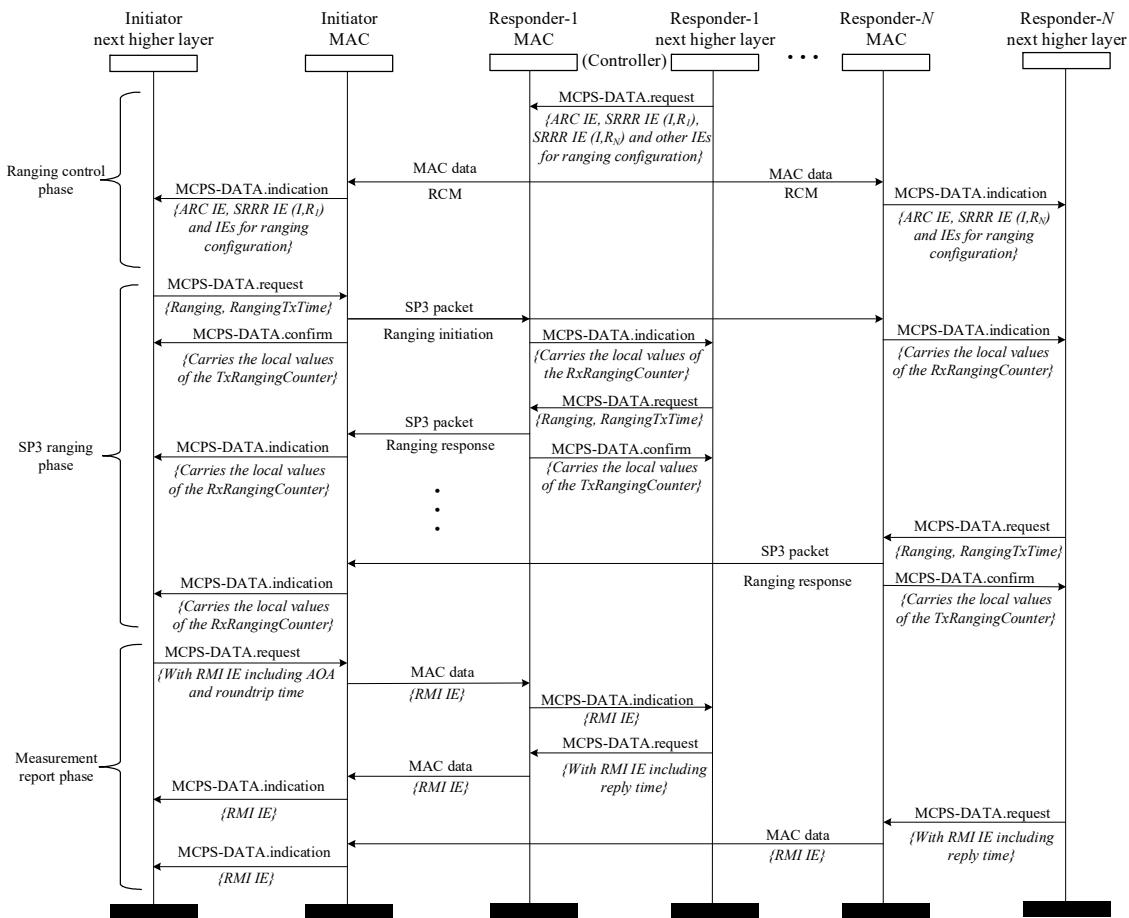


Figure 10-242—Message sequence chart for SP3 one-to-many SS-TWR

Since multi-node SP3 ranging is based on the scheduling determined by the next higher layer of the controller, each time slot is allocated to a particular RDEV to use. With a fixed ranging procedure indicated by the Ranging Round Usage field of the ARC IE (described in 10.32.9.1), the RDEV knows when the SP3 ranging phase will be completed, and can configure the packet format properly for the measurement report phase via the MLME-STS.request primitive.

After the SP3 ranging phase, ERDEVs are scheduled in the measurement report phase to send the requested information. In the example in Figure 10-243, the initiator conveys the AOA and round-trip time to Responder-1 using the RMI IE (described in 10.29.8.4), and Responder-1 and Responder- N each separately embed the requested reply time in an RMI IE sent to the initiator.

The controller can also be an initiator and the corresponding message sequence chart is straightforward and is omitted here.

10.32.8.3 Ranging procedure for multi-node DS-TWR with SP3 packets

Figure 10-243 illustrates an example of one-to-many DS-TWR with SP3 packets, which is similar to Figure 10-242. The main difference is that there is a second SP3 packet in the ranging phase from the initiator. At the beginning of the ranging round, the requests are broadcast from the controller to controlees. For example, the initiator requests the AOA report from both Responder-1 and Responder-N by setting the RAOA field to 1 in the SRRR IE (described in 10.32.9.9). After the SP3 ranging, ERDEVs are scheduled to

send their reports with the requested information using RMI IEs (described in 10.29.8.4). In this example, the initiator sends its reply time and round-trip time to Responder-1, while Responder-1 and Responder- N each send an AOA report back to the initiator. The controller assumes the role of a responder in this example. The controller can alternatively be the initiator.

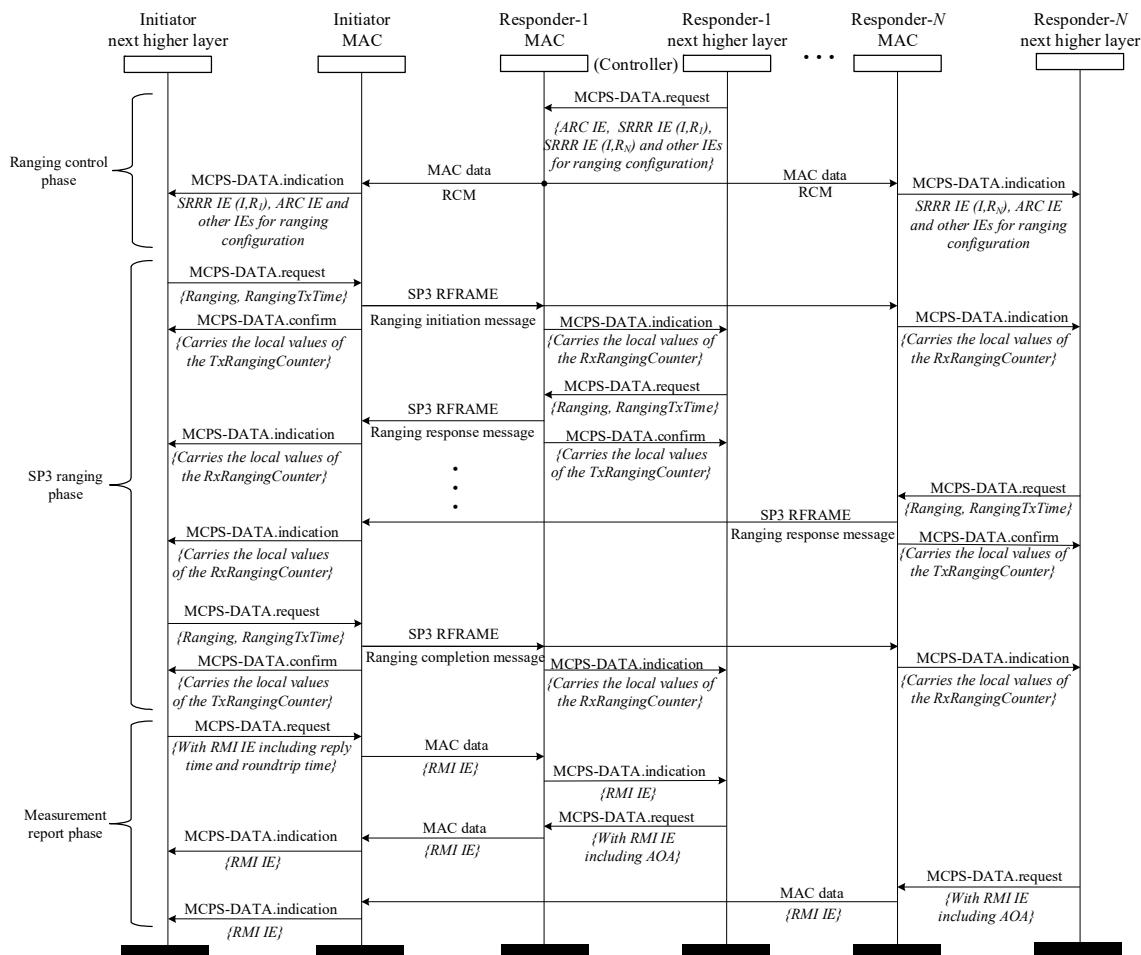


Figure 10-243—Message sequence chart for SP3 one-to-many DS-TWR

10.32.9 Nested IEs for multi-node ranging

10.32.9.1 Advanced Ranging Control IE (ARC IE)

The ARC IE is used by a controller to send the ranging configuration information to a contreee (in a unicast frame) or multiple contreees (in a broadcast frame). The ARC IE can also be used by the contreee, along with the RCR IE (described in 10.32.9.7), to send preferred ranging parameters to the controller. The Content field of the ARC IE shall be formatted as shown in Figure 10-244.

Bits: 0–1	2–3	4–5	6	7	8	9–14	15	Octets: 1	0/3	0/1	0/2	0/4
Multi-node Mode	Ranging Round Usage	STS Packet Config	Schedule Mode	Deferred Mode	Time Structure Indicator	RCM Validity Rounds	MMRCR	Content Control	Ranging Block Duration	Ranging Round Duration	Ranging Slot Duration	Session ID

Figure 10-244—ARC IE Content field format

The Multi-node Mode field value specifies whether the ranging is to be performed between a single pair of devices or is multi-node ranging involving many devices. The Multi-node Mode field shall have one of the non-reserved values specified in Table 10-163.

Table 10-163—Values of the Multi-node Mode field in the ARC IE

Multi-node Mode field value	Meaning
0	Single device to single device (unicast).
1	Multi-node one-to-many.
2	Multi-node many-to-many.
3	Reserved.

The Ranging Round Usage field specifies the use of the current ranging round and a subsequent number of ranging round(s) following the RCM as specified in the Ranging Validity Rounds field of the ARC IE. The Ranging Round Usage field shall have one of the values defined in Table 10-164.

Table 10-164—Values of Ranging Round Usage field in the ARC IE

Ranging Round Usage field value	Selected ranging round use
0	One-way ranging (OWR), see 10.29.1.2.5.
1	Single-sided two-way ranging (SS-TWR), see 10.29.1.2.2.
2	Double-sided two-way ranging (DS-TWR), see 10.29.1.2.3.
3	Ranging ancillary information exchange, see 10.35.

The STS Packet Config field specifies the STS packet format to be used in the ranging round(s) that follow the ARC IE. The STS Packet Config field shall have one of the values defined in Table 10-165. For devices that are not HRP-ERDEV this field shall be set to zero.

Table 10-165—Values of STS Packet Config field in the ARC IE

STS Packet Config field value	Resultant STS packet configuration
0	No STS field included in the PPDU.
1	STS packet structure #1 as specified in Table 16-1.
2	STS packet structure #2 as specified in Table 16-1.
3	STS packet structure #3 as specified in Table 16-1.

The Schedule Mode field specifies whether the scheduling-based ranging or contention-based ranging is performed as per Table 10-166.

Table 10-166—Values of Schedule Mode field in the ARC IE

Schedule Mode field value	Selected ranging schedule mode and behavior
0	Contention-based ranging is used for the following ranging rounds, and the RDM IE described in 10.32.9.8 and the RCPS IE as described in 10.32.9.5 are employed to control participation.
1	Scheduling-based ranging is used for the following ranging rounds. Participation in the ranging and time slot allocation may be fixed, or controlled via the use of the RDM IE.

The Deferred Mode field specifies whether or not the deferred frame is allowed for the measurement report. If the field value is one, it indicates that ranging slots are scheduled for the transmission of deferred Data frame(s) after the ranging exchange, which should typically be used to report certain measurement information, for example TOF, reply time, and AOA. If the field value is zero, it indicates that ranging slots are not scheduled for Data frames for exchange of requested information and the requested information should be embedded in the RFRAFME, for example RRTI IE as described in 10.29.8.1.

The Time Structure Indicator field specifies the ranging time structure behavior in the following ranging rounds as per Table 10-167.

Table 10-167—Values of Time Structure Indicator field in the ARC IE

Time Structure Indicator field value	Selected ranging time structure behavior
0	The time structure is interval-based and the RIU IE described in 10.32.9.2 is used to control the ranging interval updates.
1	The time structure is block-based and the RR IE described in 10.32.9.3 and RBU IE described in 10.32.9.4 are used to control the ranging interval updates.

The RCM Validity Rounds field is an unsigned integer that specifies the number of consecutive ranging rounds controlled by the RCM.

Note that this value cannot be larger than the number of remaining ranging rounds in the current block.

The Multiple Message Receipt Confirmation Request (MMRCR) field indicates whether multiple message receipt confirmation is requested or not: if the MMRCR field value is one, it is requested, otherwise it is not. The Multiple Message Receipt Confirmation procedure is described in 10.36.

The Content Control field is formatted as per Figure 10-245, indicating presence or not of other fields in the ARC IE.

Bits: 0	1	2	3	4–7
RBDP	RRDP	RSDP	SIP	Reserved

Figure 10-245—Content Control field of the ARC IE

The RBDP field when one indicates the presence of the Ranging Block Duration field, or not present when zero.

The RRDP field when one indicates the presence of the Ranging Round Duration field, or not present when zero.

The RSDP field when one indicates the presence of the Ranging Slot Duration field, or not present when zero.

The SIP field when one indicates the presence of the Session ID field, or not present when zero.

The Ranging Block Duration field is an unsigned integer that specifies the duration of a ranging block in the unit of RSTU (as defined in 10.29.1.5).

The Ranging Round Duration field is an unsigned integer that specifies the duration of the ranging round in units of ranging slots, that is the number of ranging slots in the ranging round.

The Ranging Slot Duration field is an unsigned integer that specifies the duration of a ranging slot in RSTU.

A group of ERDEVs engaged in a continuous ranging procedure that is characterized by a specific initial set of parameters is called a ranging session. A ranging session shall have only one controller and at least one initiator. Only the controller can configure the initial ranging parameters, and update them during a ranging session. The Session ID field contains a 4-octet session identifier that is unique to a session per controller. A separate set of STS seeds should be associated with each session. A set of STS seeds in this context consists of all STS seeds within a ranging session for which the same STS seed is being used, the seeds possibly being related to each other via a systematic update procedure, such as a counter. Within a set of STS seeds, it is recommended that no STS seed is used more than once.

One or more fields of duration, that is Ranging Block Duration field, Ranging Round Duration field, and Ranging Slot Duration field, may not be present in the ARC IE of the current RCM, if the ranging block structure follows the same specified duration as before, while other fields, for example Schedule Mode field and STS Packet Config field, can still be used to update corresponding ranging parameters.

10.32.9.2 Ranging Interval Update IE (RIU IE)

The RIU IE is used to update the ranging interval in interval-based mode. The RIU IE Content field shall be formatted as illustrated in Figure 10-246.

Octets: 1	4	0/2	0/2	0/1	0/1	0/2	0/1/2/4
Content Control	Block Interval	Next Round Interval	RIUM Interval	Remaining Number of RIUMs	RTW Multiplier	RTW Initial Size	Current Round Set Index

Figure 10-246—RIU IE Content field format

The Content Control field is formatted as per Figure 10-247, indicating presence or not of other fields in the RIU IE.

Bits: 0	1	2	3	4–5	6–7
NRIP	RIUMP	RTWMP	RTWISP	CRSIP	Reserved

Figure 10-247—Content Control field of the RIU IE

The NRIP field when one indicates the presence of the Next Round Interval field, or when zero that it is not present. If the round interval for the next ranging round set is zero, the Next Round Interval field can be omitted with the NRIP field set to zero.

The RIUMP field when one indicates the presence of both the RIUM Interval field and the Remaining Number of RIUMs field, or when zero that both of those fields are not present.

The RTWMP field when one indicates the presence of the RTW Multiplier field, or not present when zero.

The RTWISP field when one indicates the presence of the RTW Initial Size field, or not present when zero.

The CRSIP field indicates the presence and size of the Current Round Set Index field as per in Table 10-168.

Table 10-168—Values of CRSIP field in the RIU IE

CRSIP field value	Meaning
0	Current Round Set Index field is not present.
1	Current Round Set Index field is 1 octet.
2	Current Round Set Index field is 2 octets.
3	Current Round Set Index field is 4 octets.

The Block Interval field indicates the time remaining in RSTU (as defined in 10.29.1.5) until the start of the next ranging block relative to the start of the current packet. A value of 0xffffffff is used to indicate that the ERDEVs are to stop ranging.

The Next Round Interval field, if present, indicates the time remaining in RSTU until the start of the next ranging round relative to the start of the next ranging block.

The RIUM Interval field, if present, indicates the time remaining in RSTU until the start of the next RIUM packet relative to the start of the current packet.

The Remaining Number of RIUMs field specifies the remaining number of RIUM until the next RCM.

The RTW Multiplier field together with the RTW Initial Size field are used to specify the RCM Timing Window (RTW) in RSTU, as follows:

$$\text{RTW} = (\text{RTW Initial Size field value}) \times 2^{(\text{RTW Multiplier field value})}$$

RTW operation depends on the values of RTWMP and RTWISP as specified in Table 10-169.

Table 10-169—RTW operation based on the RTWISP and RTWMP fields

RTWMP field value	RTWISP field value	Meaning
0	0	RTW operation is disabled for the next ranging round and the controller sends the RCM without any RTW.
1	0	RTW operation is disabled for the next ranging round and the controller sends the RCM without any RTW.
0	1	RTW operation is enabled for the next ranging round and the controller sends the RCM at random timing within the RTW period. The size of RTW period is fixed at the value specified by the RTW Initial Size field.
1	1	RTW operation is enabled for the next ranging round and the controller sends the RCM at random timing within the RTW period. The size of RTW is determined by the RTW Initial Size field and RTW Multiplier field.

The Current Round Set Index field, if present, indicates the ranging round set index. The ranging round set index is a global counter incrementing across the ranging blocks.

The procedures for using the RIU IE are defined in 10.32.3.2.

10.32.9.3 Ranging Round IE (RR IE)

The RR IE may be used to signal ranging round information for the current ranging round or ranging round information for the next ranging round according to the description in 10.32.3.3. The Content field of the RR IE shall be formatted as shown in Figure 10-248.

Octets: 2	Bits: 0	1–15	Octets: 2
Ranging Block Index	Hopping Mode	Round Index	Transmission Offset

Figure 10-248—RR IE Content field format

The Ranging Block Index field specifies the index of the ranging block.

The Hopping Mode field specifies the hop mode for the ranging block, where zero means no hopping and one means hopping.

The Round Index field specifies the ranging round index for the ranging block.

The Transmission Offset field specifies the value of transmission offset of the ranging round in the block, in RSTU. This offset shall be at most the ranging slot duration minus the packet duration.

The RR IE is only used in block-based mode. Devices participating in the ranging exchange have either (a) pre-negotiated a hopping sequence that is known to all devices, or (b) have exchanged all the information necessary such that each device can generate the hopping sequence.

10.32.9.4 Ranging Block Update IE (RBU IE)

The RBU IE is sent by the controller to the controlees to signal an update to the ranging block structure. If the final message in the ranging messages sequence is sent by the controller, then the RBU IE will be sent in that message. However, if the final message in the ranging messages sequence is sent by a conteree, then the RBU IE will be sent by the controller in the following RCM. The Content field of the RBU IE shall be formatted as shown in Figure 10-249.

Octets: 1	3	1/0	2/0
Relative Ranging Block Index	Updated Block Duration	Updated Ranging Round Duration	Updated Slot Duration

Figure 10-249—RBU IE Content field format

The Relative Ranging Block Index field indicates the number of ranging blocks with the current ranging block structure before switching to the new ranging block structure.

The Updated Block Duration field is an unsigned integer used to indicate the new ranging block duration in RSTU (as defined in 10.29.1.5). The RBU IE can be used to signal the termination of the ranging message exchange. This is achieved by setting the Updated Ranging Block Duration field in the RBU IE to zero.

The Updated Ranging Round Duration field is an unsigned integer used to specify the value of the ranging round duration in the new ranging block structure as an integer multiple of ranging slot duration.

The Updated Slot Duration field is an unsigned integer used to specify the value of the ranging slot duration in the new ranging block structure in RSTU.

NOTE—The RBU IE can be used to update the block duration only, in which case the Updated Ranging Round Duration and Updated Slot Duration fields will not be present. The RBU IE can be included in an RCM. When the RBU IE is used to update the block, round, and slot durations its size will be seven octets. When the RBU IE is used to update only the ranging block duration, the Updated Ranging Round Duration field and the Updated Slot Duration field will not be present, and the size of the IE will be four octets.

10.32.9.5 Ranging Contention Phase Structure IE (RCPS IE)

The RCPS IE provides the slot indices for the various phases of the ranging round when schedule mode is contention-based. The Content field of the RCPS IE shall be formatted as shown in Figure 10-250.

Octets: 1	variable
CP Table Length	CP Table

Figure 10-250—RCPS IE Content field format

The CP Table Length field specifies the number of CP Table Elements in the CP Table field. The number of CP Table Elements shall be set to equal the number of contention phases in the ranging round.

The CP Table field contains a number of CP Table Elements, each of which is structured as per Figure 10-251, with fields as described below.

Bits: 0–1	2–8	9–15
Phase Indicator	Ranging Slot Index to Start	Ranging Slot Index to End

Figure 10-251—CP Table Element

The Phase Indicator field selects whether the phase being described is used for ranging transmissions or measurement reports, as specified in Table 10-170.

Table 10-170—Values of the Phase Indicator field in the RCPS IE

Phase Indicator field value	Meaning
0	This phase is used by the initiators to contend for ranging transmissions.
1	This phase is used by the responders to contend for ranging transmissions.
2	This phase is used by participated RDEVs to contend for measurement report.
3	Reserved.

The Ranging Slot Index to Start field and Ranging Slot Index to End field together specify the boundary of the phase being described. The range of different phases shall not overlap.

10.32.9.6 Ranging Contention Maximum Attempts IE (RCMA IE)

The RCMA IE specifies the maximum number of attempts at responding when contention is being used. The Content field of the RCMA IE shall be formatted as shown in Figure 10-252.

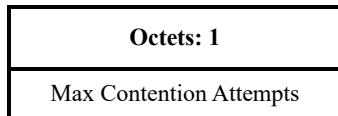


Figure 10-252—RCMA IE Content field format

The Max Contention Attempts field specifies the maximum number of attempts. Upon transmission, the value is provided by the higher layer. Upon reception, the value shall be used as the maximum number of contention attempts. This value shall be less than or equal to the RCM Validity Rounds as specified by the ARC IE (described in 10.32.9.1).

10.32.9.7 Ranging Change Request IE (RCR IE)

The RCR IE is sent by a contee to request the controller to make a change to the ranging parameters. In interval-based mode, the RCR IE shall be accompanied by an ARC IE (described in 10.32.9.1) and/or an RIU IE (described in 10.32.9.2). In block-based mode the RCR IE shall be accompanied by an RR IE (described 10.32.9.3) and/or an RBU IE (described in 10.32.9.4). Other IEs may also be included for other reasons. Since the preferred parameters and intervals from contee(s) are included in the ARC IE and the RIU IE, the RCR IE has no Content field. The controller is responsible for acting on the change request, and notifying this in a subsequent RCM.

10.32.9.8 Ranging Device Management IE (RDM IE)

The RDM IE is used by the controller to control the devices participating in a set of ranging rounds when the controller knows the device identities. The Content field of the RDM IE shall be formatted as shown in Figure 10-253.

Bits: 0	1	2–7	Octets: variable
SIU	Address Size	RDM List Length	RDM List

Figure 10-253—RDM IE Content field format

The SIU field indicates whether the Slot Index field of the RDM List element is used (when the SIU field is one) or not (when the SIU field is zero). When the SIU field is zero, the RDM IE is used to assign the ranging role, that is initiator or responder, to contees for contention-based ranging. When the SIU field is one, the RDM IE is used to allocate time slots and assign the ranging roles of contees for the scheduling-based ranging.

The Address Size field specifies the size of the addresses used in the RDM List field. If the Address Size field is zero, all addresses in the RDM List elements are short addresses. If the Address Size field is one, all addresses are extended addresses.

The RDM List Length field indicates the number of elements in the RDM List field, each of which is formatted as per Figure 10-254. This is the number of participating ERDEVs selected by the RDM IE, and, when the SIU field is one, the number of slots assigned by the RDM IE.

Bits: 0	1–7	Octets: 2/8
Ranging Role	Ranging Slot Index	Address

Figure 10-254—RDM List element format

The Ranging Role field specifies whether the selected device is to be an initiator or a responder. When the Ranging Role field has a value of zero the selected device is a responder. When the Ranging Role field has a value of one the selected device is an initiator.

The Ranging Slot Index field is used (when the SIU field is one) to assign a slot index to the device identified by the address field. When the SIU field is zero this field is not used and shall be ignored upon receipt.

The Address field identifies each participating device. The size of the Address field is specified by the Address Size field of the RDM IE. A network of mixed address size devices can be catered for by using two RDM IEs, one for the short address devices and the other for the extended address devices.

The RDM IE can be used by the controller to exchange scheduling information among the ERDEVs for a set of ranging rounds specified by the same RCM. Upon reception of the RCM, a conteree knows whether it is selected to participate in the ranging round(s).

10.32.9.9 SP3 Ranging Request Reports IE (SRRR IE)

The SRRR IE is used to indicate a request for report of AOA and/or reply time and/or round-trip time measurement from a requester to a provider. The Content field of the SRRR IE shall be formatted as shown in Figure 10-255.

Bits: 0–1	2–3	4	5	6	7	Octets: 0/2/8	0//2/8
Requester Address Size Specifier	Provider Address Size Specifier	RAOA	RRT	RRTT	RTOF	Requester Address	Provider Address

Figure 10-255—SRRR IE Content field format

The Requester Address Size Specifier field specifies the size of the Requester Address field, as per the definition in Table 10-149.

The Provider Address Size Specifier field specifies the size of the Provider Address field, as per the definition in Table 10-149.

The RAOA field indicates that a report of AOA is required when the RAOA field is one, and not required when the RAOA field is zero.

The RRT field indicates that a report of reply time is required when the RRT field is one, and not required when the RRT field is zero.

The RRTT field indicates that a report of round-trip time is required when the RRTT field is one, and not required when the RRTT field is zero.

The RTOF field indicates that a report of TOF is required when the RTOF field is one, and not required when the RTOF field is zero.

The Requester Address field is the address of the device whose transmitted signal AOA is to be measured, or the device initiating the ranging.

The Provider Address field is the address of the device measuring the AOA.

One or more SRRR IEs may be conveyed in a single RCM.

For the use case with many initiators and many responders, both address fields are needed to distinguish a pair of devices.

For multi-node SP3 ranging (i.e., only one initiator and multiple responders), if the controller is also the initiator requesting the report from the controles (responders), the SRRR IE in the RCM does not need to incorporate the address field of the requester, since responders implicitly know that requests are from the controller (initiator).

In unicast SP3 ranging, the SRRR IE can be sent without requester address or provider address fields. In this case the MHR source address identifies the requester and the provider is the receiving device.

10.33 Ranging: Authenticated challenge-response ranging

10.33.1 Overview of ACRR

The use and support of the procedures and associated IEs in this subclause are optional. This subclause provides the MAC functional description for authenticated challenge-response ranging (ACRR) based on TOF measurement and distance bounding by distance commitment on data payload between ranging devices acting as verifier and prover. ACRR uses the Ranging Verifier command defined in 10.33.7.1 and the Ranging Prover command defined in 10.33.7.2. These contain verifiable ranging data for the validation of the ranging exchange and the corresponding TOF. The generation and verification of these frames is under the control of the MCPS-RANGING-VERIFIER and MCPS-RANGING-PROVER primitives defined in 10.33.8.1 and 10.33.8.2, which utilize and rely on the security services provided by Clause 9. Information with implementation details and analysis is provided in sections 1 and 2 of “Authenticated Ranging of IEEE 802.15.4” [B6].

The MCPS-RANGING-VERIFIER.request and MCPS-RANGING-PROVER.request primitives each include a SecurityParams parameter for the next higher layer to select the security level, a DistanceCommitmentLevel parameter for the next higher layer to select the level of distance commitment, an AcrrMode parameter for the next higher layer to select the ACRR ranging method, and a RawMode parameter to control whether the FCS check is enabled or disabled for bit error tolerant ACRR.

MCPS-RANGING-VERIFIER.indication and MCPS-RANGING-PROVER.indication primitives provide the challenge and response data together with the ranging counter information to the next higher layer of verifier and prover. The MCPS-RANGING-VERIFIER.confirm and MCPS-RANGING-PROVER.confirm primitives signal the end of the exchange and the disabling of the ranging function, and they provide a status parameter to indicate success or other error condition such as a timeout.

For single-sided ACRR, the MLME in the responder enables the PHY fixed reply time capability. For DS-TWR the reply time is communicated in a separate secure exchange of information after the ranging exchange and a fixed reply time is not required.

Figure 10-256 illustrates the basic principle of ranging with a challenge and a response exchange between a verifier and a prover with fixed reply time at the prover.

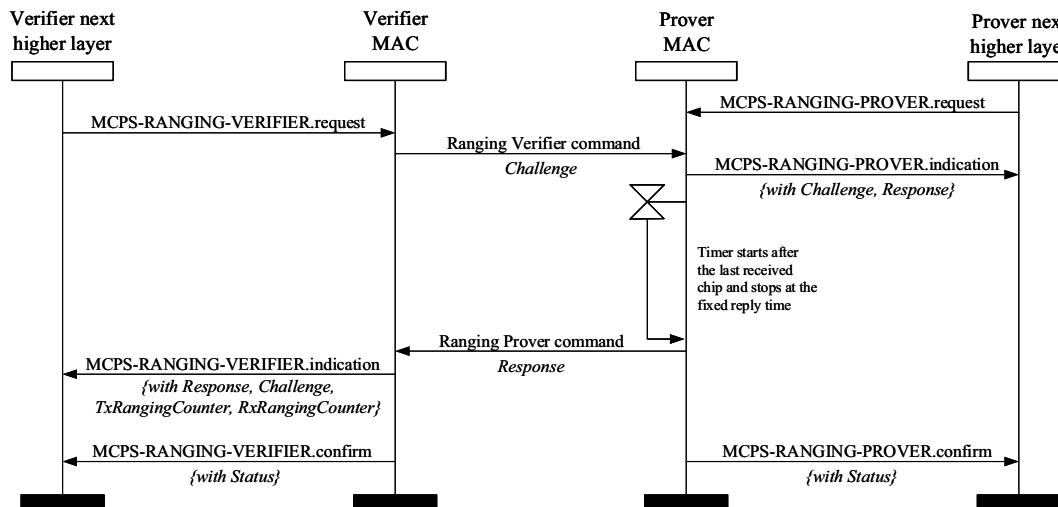


Figure 10-256—Message sequence chart for ACRR with fixed reply time

The prover next higher layer invokes the MCPS-RANGING-PROVER.request primitive to prepare the receiver for the ranging exchange.

The verifier next higher layer initiates the ranging exchange by invoking the MCPS-RANGING-VERIFIER.request primitive. The verifier MAC sends a Ranging Verifier command with the challenge and the prover MAC returns a Ranging Prover command with its response after a fixed reply time specified by the corresponding PHY fixed reply time attribute in Table 12-7. For the LRP-ERDEV, the fixed reply time is specified in 19.8.

The challenge and response data as well as other configuration parameters depend on the ACRR mode and are described in 10.33.5 for each case.

If the Challenge is not received at the prover device with the Ranging Verifier command both devices will timeout with the confirm primitive and status of TRANSACTION_EXPIRED as shown in Figure 10-257.

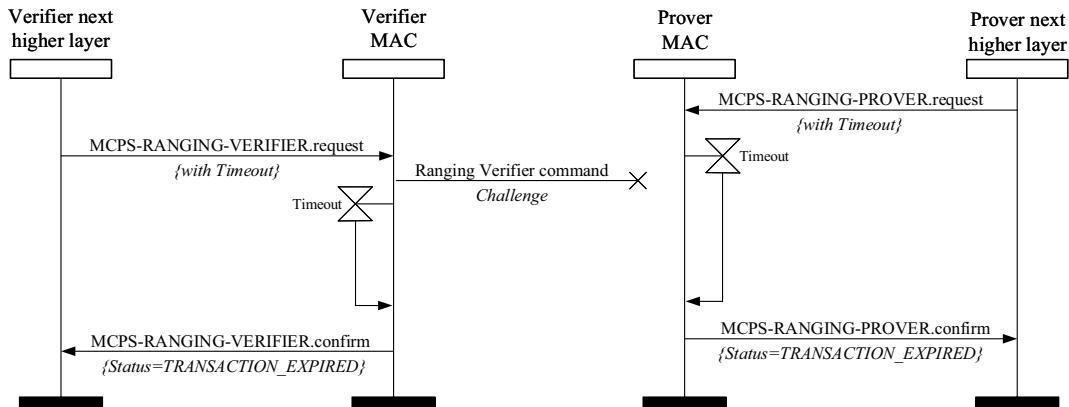


Figure 10-257—Message sequence chart for basic ACRR with challenge timeout

If the Ranging Prover command is not received at the verifier device the prover device will still indicate a successful data transfer to the prover next higher layer, but the verifier device will timeout with the confirm primitive and status of TRANSACTION_EXPIRED as shown in Figure 10-258.

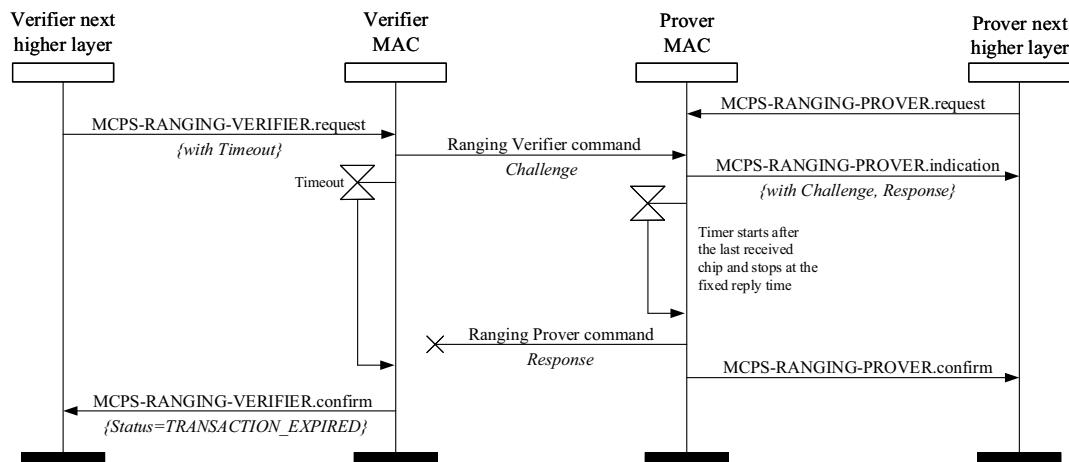


Figure 10-258—Message sequence chart for basic ACRR with response timeout

10.33.2 Reception while doing ACRR

When a device is configured to use raw mode using the RawMode parameter of the MCPS-RANGING-VERIFIER.request or MCPS-RANGING-PROVER.request primitives, the frame is processed without conducting any of the filtering described in this subclause.

10.33.3 Security levels

10.33.3.1 General

ACRR supports various security levels defining the length of the cryptographic challenge and response data as per Table 10-171. Validating the authenticity of the response relies on the services provided by Clause 9.

Table 10-171—Security levels for ACRR

Security level	Length of challenge data, length of response data (bits)
1 and 5	32
2 and 6	64
3 and 7	128

10.33.3.2 Security levels in case of tolerance of bit errors

The security level in case of tolerance of bit errors in the cryptographic challenges and responses is defined by the following formula:

$$\text{Security level}(L, k) = -\log_2 \left(\frac{\sum_{n=0}^k \binom{L}{n}}{2^L} \right)$$

where L is the length of the cryptographic challenge and response and k is the number of the desired maximum allowed bit errors.

Table 10-172 provides the maximum allowed bit errors for the different security levels for challenge and response lengths of 64, 128, and 256 bits. The prover next higher layer invokes the MCPS-RANGING-PROVER.request primitive to prepare the receiver for the SS-TWR with one-way authentication with the desired security level and distance commitment level.

Table 10-172—Example of security levels for ACRR with tolerance of bit errors

Security level	Length of challenge data, length of response data (bits)	Maximum allowed bit errors (bits)
1 and 5	64	8
2 and 6	128	15
3 and 7	256	31

The MCPS-RANGING-VERIFIER.request primitive has a ChallengeLength parameter, and the MCPS-RANGING-PROVER.request primitive has a ResponseLength parameter, used respectively to specify the length of the challenge and response to be generated and transmitted by the MAC sublayer. For these transmissions of challenge and response data, the security services of Clause 9 are not used, that is the security level is 0.

For larger challenges and responses, the formula should be used by the higher layer to compute the number of maximum allowed bit errors in order to verify the desired security level of the received challenge and response.

The rationale and the derivation of the mathematical formula of the maximum allowed bit errors in the cryptographic challenge and response are provided in Section 3 of “Authenticated Ranging of IEEE 802.15.4” [B6].

10.33.4 Coordinating ranging methods and security levels

For successful ACRR interworking the verifier and prover devices need to be aligned with respect to the security levels and ranging methods to use. The Authenticated Challenge-Response Ranging Control IE (ACRRC IE) defined in 10.33.6.1 may be used to coordinate these values, or this may be done by pre-agreement or some other out-of-band means.

The MCPS-RANGING-VERIFIER.request and MCPS-RANGING-PROVER.request primitives' AccrIeIncluded parameter enables the transmission of the ACRRC IE in the Ranging Verifier command or Ranging Prover command for the next transmission to request the ACRR mode and/or security level to be used by the receiving MAC sublayer. In such case, the receiving MAC sublayer shall use the values received in the ACRRC IE instead of any previously set ones for its next transmission (response), unless the ACRRC IE values are specifying a lower security level in which case the ACRRC IE shall be ignored. The security level given in the MCPS-RANGING-VERIFIER.request or MCPS-RANGING-PROVER.request sets the lower bound for the security level to be performed by the device security services.

10.33.5 ACRR procedures

10.33.5.1 General

ACRR can be realized with SS-TWR and DS-TWR. The SS-TWR modes operate with fixed reply times. The DS-TWR modes do not use a fixed reply time and instead perform a secure exchange of ranging counter information after the ranging exchange.

10.33.5.2 ACRR based SS-TWR with one-way authentication

Figure 10-259 shows the message sequence for SS-TWR with one-way authentication.

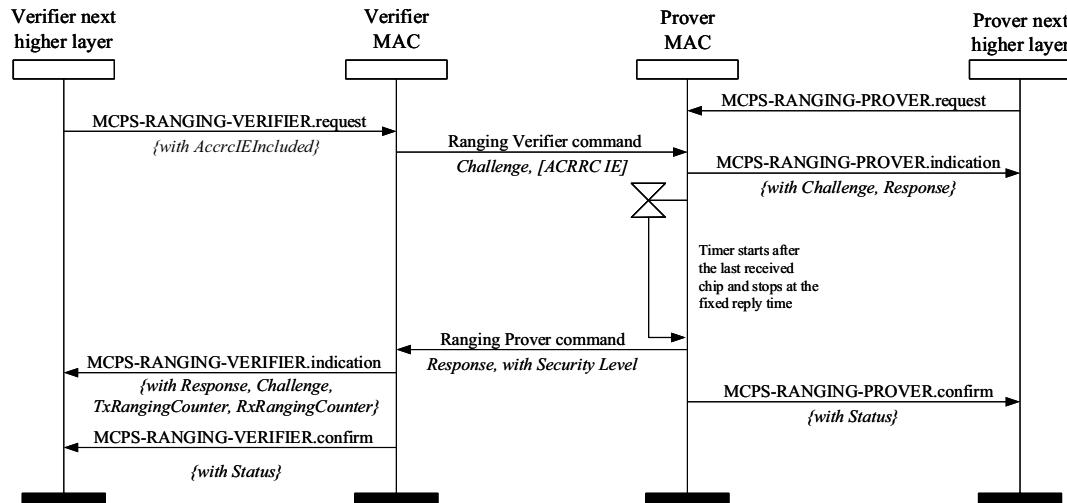


Figure 10-259—Message sequence chart for SS-TWR with one-way authentication

The verifier next higher layer initiates the ranging exchange by invoking the MCPS-RANGING-VERIFIER.request with the desired security level and distance commitment level. The verifier MAC generates a fresh VChallenge of length according to the security level and transmits it in the Challenge field of the Ranging Verifier command. Optionally an ACRRC IE can be used, by enabling it in the MCPS-RANGING-VERIFIER.request, to request a change to the security level used by the prover MAC for its response.

The prover MAC receives the VChallenge and starts the timer of the fixed reply time procedure. After the procedure completes and the timer stops, the prover MAC layer returns a Ranging Prover command containing, in its Response field, the contents of the Challenge field of the received Ranging Verifier command, with the specified security level indicated in the MCPS-RANGING-PROVER.request. The MCPS-RANGING-PROVER.indication primitive also indicates the received VChallenge for the next higher layer use.

If the ACRRC IE is used within the Ranging Verifier command and a different security level is specified, then the prover MAC shall use the security level value in the ACRRC IE signaled by the verifier, unless the value is specifying a lower security level, in which case the ACRRC IE shall be ignored. If the received security level is zero, the prover shall not respond and shall abort the operation, issuing the MCPS-RANGING-PROVER.confirm with a status of IMPROPER_SECURITY_LEVEL.

Upon reception of the Ranging Prover command, the verifier MAC indicates the transmitted challenge and received response to the next higher layer and confirms the status.

Table 10-173 defines the content of the MAC commands.

Table 10-173—Content of challenge and response for SS-TWR with one-way authentication

Message	Content of the Challenge field in the Ranging Verifier command	Content of the Response field in the Ranging Prover command
1	VChallenge	
2		VChallenge

10.33.5.3 ACRR based SS-TWR with one-way authentication and tolerance of bit errors in the challenges

Figure 10-260 describes the message sequence for SS-TWR with one-way authentication and tolerance of bit errors in the cryptographic challenges exchanged between the verifier and the prover.

The prover next higher layer invokes the MCPS-RANGING-PROVER.request primitive to prepare the receiver for the ranging exchange with SS-TWR one-way authentication, desired response length, distance commitment level, and the RawMode parameter set to TRUE to have the FCS check ignored (i.e., tolerance of bit errors in the received challenge and response data).

The verifier next higher layer initiates the ranging exchange by invoking the MCPS-RANGING-VERIFIER.request with the desired challenge length, distance commitment level, and the RawMode set to TRUE. The verifier MAC generates a fresh VChallenge of length according to the security level in case of tolerance of bit errors and transmits it in the Challenge field of a Ranging Verifier command.

The prover MAC receives the VChallenge, starts the timer of the fixed reply time procedure and generates a fresh PChallenge. The PChallenge is an unguessable cryptographically generated random sequence of octets with its length selected by the ResponseLength parameter of the MCPS-RANGING-PROVER.request primitive. After the procedure completes and the timer stops, the prover MAC transmits a Ranging Prover command containing the PChallenge in its Response field without using the MAC level security, that is security level zero. The PChallenge and the received VChallenge are delivered to the next higher layer via the MCPS-RANGING-PROVER.indication primitive, and the status is indicated by the MCPS-RANGING-PROVER.confirm primitive.

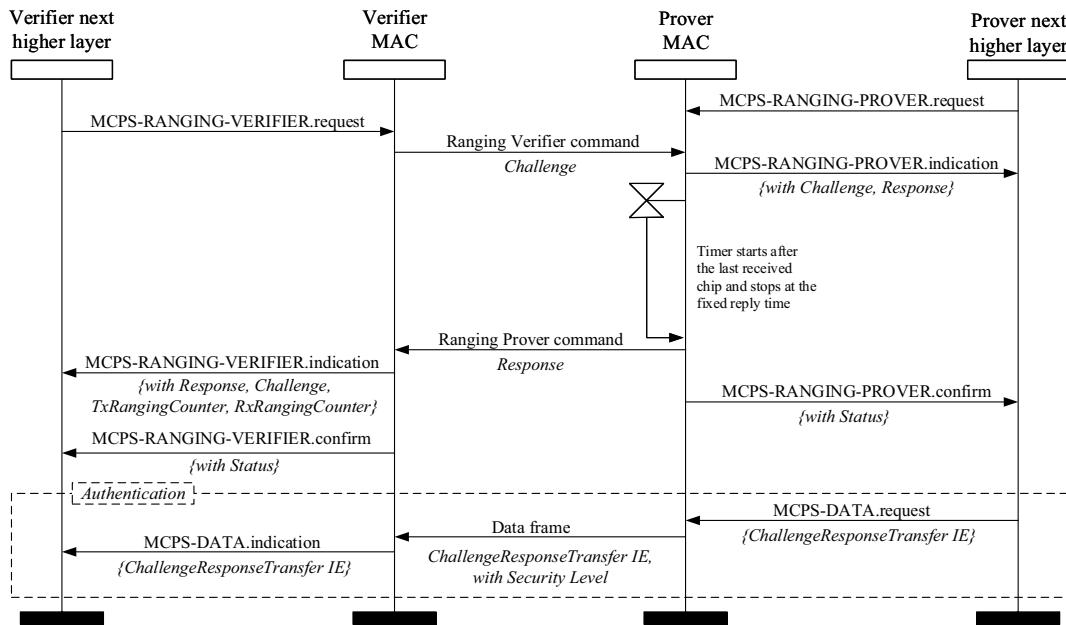


Figure 10-260—Message sequence chart SS-TWR with one-way authentication and tolerance of bit errors

To verify the integrity of the measurement at the verifier, the prover next higher layer invokes the MCPS-DATA.request primitive to transmit a message with the ChallengeResponseTransfer IEs containing the received VChallenge and PChallenge with the desired security level. If the length of the challenge and response is such that including two ChallengeResponseTransfer IEs in the same frame would exceed the capability of the PHY to send the frame, then two separate frames are employed. The verifier MAC receiving a message with a single ChallengeResponseTransfer IE knows to expect a subsequent transmission with the second ChallengeResponseTransfer IE. A security level of one, two, or three provides the integrity of the challenge and the response. This data is preferably sent in-band with higher data coding gain mode or by an out-of-band mechanism, for instance using a different radio.

Table 10-174 defines the content of the MAC commands.

Table 10-174—Content of challenge and response for SS-TWR with one-way authentication and tolerance of bit errors

Message	Content of the Challenge field in the Ranging Verifier command	Content of the Response field in the Ranging Prover command
1	VChallenge	
2		PChallenge

10.33.5.4 ACRR based DS-TWR with one-way authentication

Figure 10-261 describes the message exchange for DS-TWR with one-way authentication without a fixed reply time. This mode is intended for ranging devices that do not support a fixed reply time with the attribute *phyLrpUwbFixedReplyTimeSupported* equal to FALSE or have longer post-processing time during frame reception.

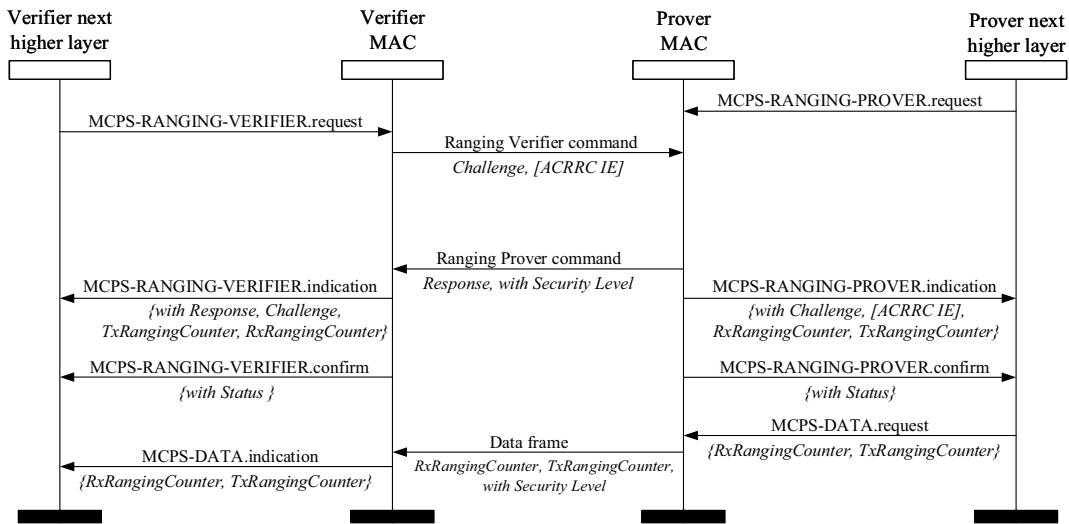


Figure 10-261—Message sequence chart for DS-TWR with one-way authentication

The prover next higher layer invokes the MCPS-RANGING-PROVER.request primitive to prepare the receiver for DS-TWR with one-way authentication with the desired security level and distance commitment level.

The verifier next higher layer initiates the ranging exchange by invoking the MCPS-RANGING-VERIFIER.request for DS-TWR with one-way authentication with the desired security level and distance commitment level. The verifier MAC generates a fresh VChallenge of length according to the security level and transmits it in the Challenge field of the Ranging Verifier command. Optionally, the ACRRIC IE can be used by enabling it in the MCPS-RANGING-VERIFIER.request to communicate the security level that the prover MAC sublayer shall use for its next response command message. The TxRangingCounter is confirmed to the next higher layer.

The prover MAC receives the VChallenge, indicates it to the next higher layer, and confirms the RxRangingCounter to the next higher layer. Then it returns a Ranging Prover command containing the received VChallenge in its Response field with the security level set by the MCPS-RANGING-PROVER.request or received from the ACRRIC IE (if used). It also confirms the TxRangingCounter to the next higher layer.

Upon reception of the Ranging Prover command, the verifier MAC indicates the VChallenge and received VChallenge to the next higher layer and confirms the RxRangingCounter.

To complete the ranging exchange, a Data frame is initiated by the prover including the ranging counters with security level.

NOTE—A security level of one, two, or three is sufficient to protect the integrity.

Table 10-175 defines the content of the MAC commands.

Table 10-175—Content of challenge and response for DS-TWR with one-way authentication

Message	Content of the Challenge field in the Ranging Verifier command	Content of the Response field in the Ranging Prover command
1	VChallenge	
2		VChallenge

10.33.5.5 ACRR based SS-TWR with mutual authentication

Figure 10-262 describes the message exchange for SS-TWR with mutual authentication and fixed reply time.

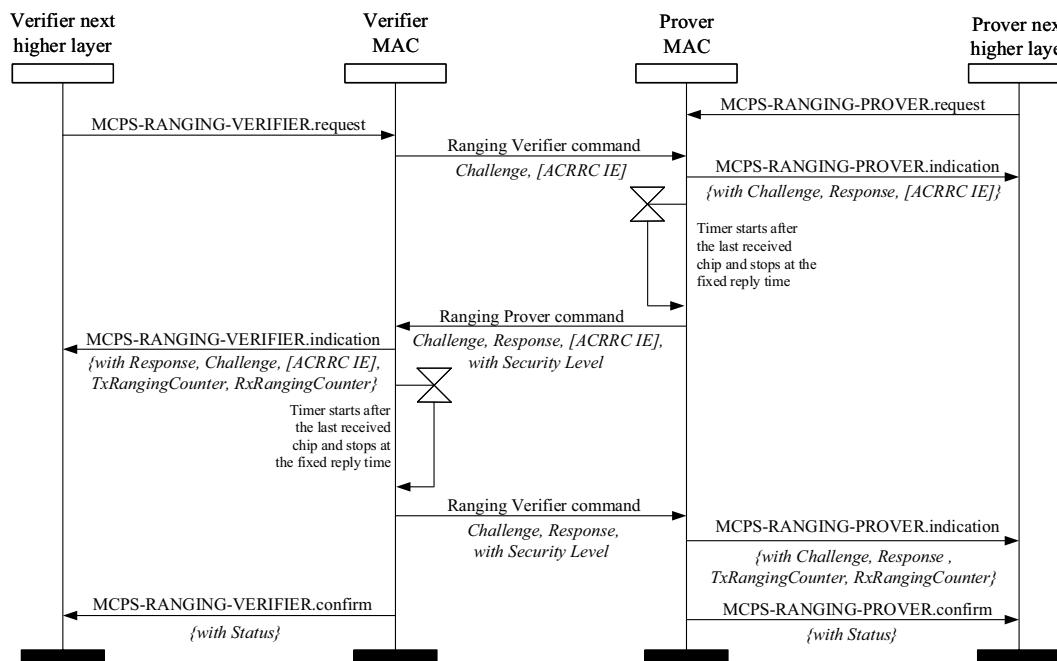


Figure 10-262—Message sequence chart for SS-TWR with mutual authentication

The prover next higher layer invokes the MCPS-RANGING-PROVER.request primitive to prepare the receiver for SS-TWR with mutual authentication exchange with the desired security level and distance commitment level.

The verifier next higher layer initiates the ranging exchange by invoking the MCPS-RANGING-VERIFIER.request with the desired security level and distance commitment level. The verifier MAC generates a fresh VChallenge of length according to the security level and transmits it in the Challenge field of the Ranging Verifier command. Optionally the ACRRC IE can be used by enabling it in the MCPS-RANGING-VERIFIER.request to request a change to the security level used by the prover MAC for its response. In a similar way, the ACRRC IE can be used by enabling it in the MCPS-RANGING-PROVER.request to request a change to the security level used by the verifier MAC for its response.

The prover MAC receives the VChallenge, starts the timer of the fixed reply time procedure, and generates a fresh PChallenge. After the procedure completes and the timer stops, the prover MAC returns a Ranging

Prover command containing the PChallenge in its Response field and the received VChallenge in its Challenge field with the security level set by the MCPS-RANGING-PROVER.request or received from the ACRRC IE (if used).

After the reception of the Ranging Prover command, the verifier MAC starts the timer of the fixed reply time procedure and indicates the received PChallenge and VChallenge to the next higher layer. After the procedure completes and the timer stops, the verifier MAC returns a Ranging Verifier command containing the received PChallenge in its Response field and the VChallenge in its Challenge field with the security level set by the MCPS-RANGING-VERIFIER.request or received from the ACRRC IE (if used). Security levels of one, two, or three are recommended to verify the integrity of the exchanged challenges and responses.

After the reception of the Ranging Verifier command, the prover MAC indicates the received VChallenge and PChallenge, and confirms the status to the next higher layer.

Table 10-176 defines the content of the MAC commands.

Table 10-176—Content of challenge and response for SS-TWR with mutual authentication

Message	Content of the Challenge field in the Ranging Verifier command	Content of the Response field in the Ranging Prover command
1	VChallenge	
2		PChallenge, VChallenge
3	VChallenge, PChallenge	

10.33.5.6 ACRR based SS-TWR with mutual authentication and tolerance of bit errors in the challenges

Figure 10-263 describes the message exchange for SS-TWR with mutual authentication and tolerance of bit errors in the cryptographic challenge and response between the verifier and the prover.

The prover next higher layer invokes the MCPS-RANGING-PROVER.request primitive to prepare the receiver for SS-TWR with mutual authentication exchange with the desired response length, distance commitment level, and the RawMode parameter set to TRUE to have the FCS check ignored (i.e., tolerance of bit errors in the received challenge and response data).

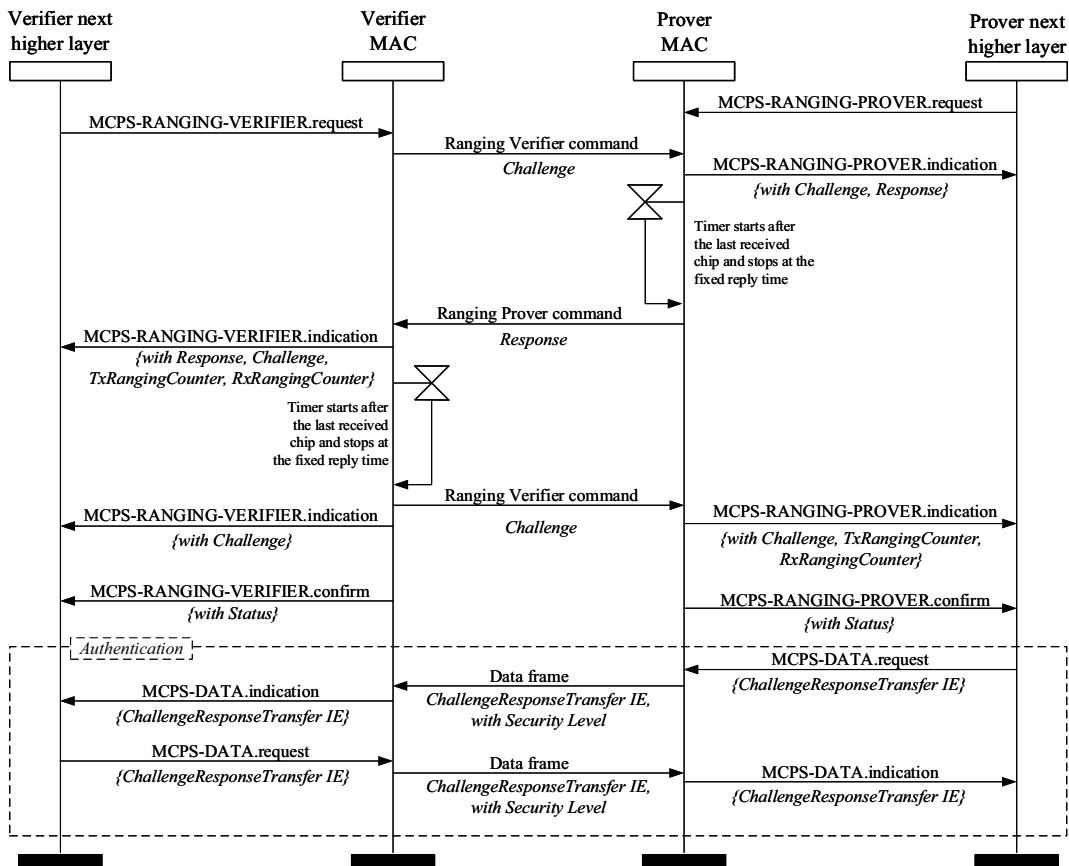


Figure 10-263—Message sequence chart for SS-TWR with mutual authentication and tolerance of bit errors

The verifier next higher layer initiates the ranging exchange by invoking the MCPS-RANGING-VERIFIER.request with the desired challenge length and distance commitment level. The verifier MAC generates a fresh VChallenge₁ of length according to the desired security level in case of tolerance of bit errors and transmits it in the Challenge field of the Ranging Verifier command.

The prover MAC receives the VChallenge₁, starts the timer of the fixed reply time procedure and generates a fresh PChallenge. After the procedure completes and timer stops, the prover MAC returns a Ranging Prover command containing in its Response field, the PChallenge of length according to the desired security level in case of tolerance of bit errors.

The verifier MAC receives the PChallenge, starts the timer of the fixed reply time procedure, indicates the received VChallenge₁ to the next higher layer, and generates a fresh VChallenge₂ of length according to the desired security level in case of tolerance of bit errors. After the procedure completes and the timer stops, the verifier MAC returns a Ranging Verifier command with VChallenge₂ in its Challenge field and confirms the status to the next higher layer. The prover MAC receives the Ranging Verifier command, indicates the received VChallenge₂ and confirms the status to the next higher layer.

With the fourth and fifth messages of the sequence the verifier and the prover verify the integrity of the measurement and provide mutual authentication. The fourth message conveys ChallengeResponseTransfer IEs containing the received VChallenge₁ and PChallenge, which the prover device sends to the verifier device with security level 1 to 7. The fifth message conveys the ChallengeResponseTransfer IE containing

the received VChallenge₂ and PChallenge with security level 1 to 7 transmitted by the verifier device. If the length of the challenge and response data is such that including two ChallengeResponseTransfer IEs in the same frame would exceed the capability of the PHY to send the frame, then two separate frames are employed. The MAC receiving a message with a single ChallengeResponseTransfer IE knows to expect a subsequent transmission with the second ChallengeResponseTransfer IE. These messages are preferably sent in-band with higher data coding gain or by an out-of-band mechanism, for instance using a different radio. Table 10-177 defines the content of the MAC commands.

Table 10-177—Content of challenge and response for SS-TWR with mutual authentication

Message	Content of the Challenge field in the Ranging Verifier command	Content of the Response field in the Ranging Prover command
1	VChallenge ₁	
2		PChallenge
3	VChallenge ₂	

10.33.5.7 ACRR based DS-TWR with mutual authentication

DS-TWR with mutual authentication makes use of two instances of SS-TWR with one-way authentication without a fixed reply time. This ACRR mode is intended for ranging devices that do not support a fixed reply time (the attribute *phyLrpUwbFixedReplyTimeSupported* equals FALSE) or that require longer post-processing time during frame reception and therefore need to exchange ranging counter information.

Figure 10-264 describes the message exchange for DS-TWR with mutual authentication without a fixed reply time.

The verifier performs an SS-TWR with one-way authentication with the prover as described in 10.33.1 and both confirm the corresponding ranging counters for the next higher layer. Then the prover performs an SS-TWR with one-way authentication with the verifier as well and both confirm the corresponding ranging counters.

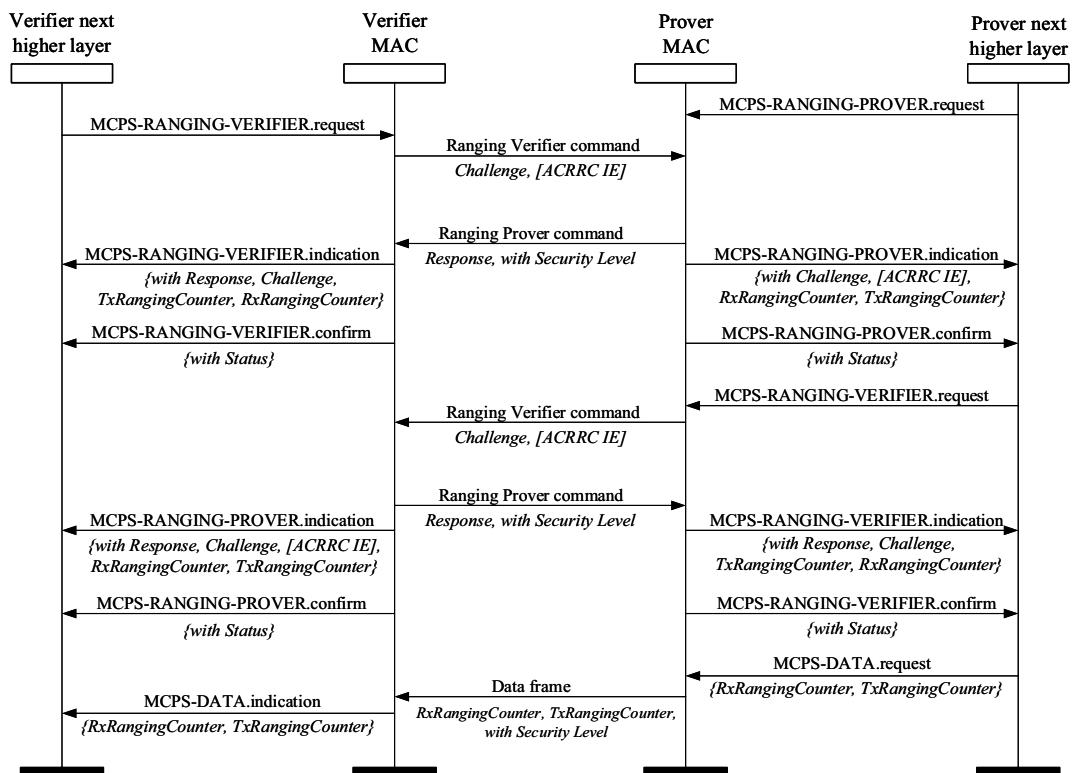


Figure 10-264—Message sequence chart for DS-TWR with mutual authentication

The DS-TWR with mutual authentication completes with a Data frame initiated by the prover containing the ranging counters with security level.

NOTE—Security levels of one to three are sufficient to verify the integrity of the ranging counter values.

Table 10-178 summarizes content of the Ranging Verifier commands and Ranging Prover commands exchanged during DS-TWR with mutual authentication.

Table 10-178—Content of challenge and response for DS-TWR with mutual authentication

Message	Content of the Challenge field in the Ranging Verifier command	Content of the Response field in the Ranging Prover command
1	VChallenge1	
2		VChallenge1
3	VChallenge2	
4		VChallenge2

10.33.5.8 ACRR based SS-TWR with one-way authentication for multiple nodes

Figure 10-265 shows the message exchange for SS-TWR with one-way authentication with one verifier and multiple prover devices.

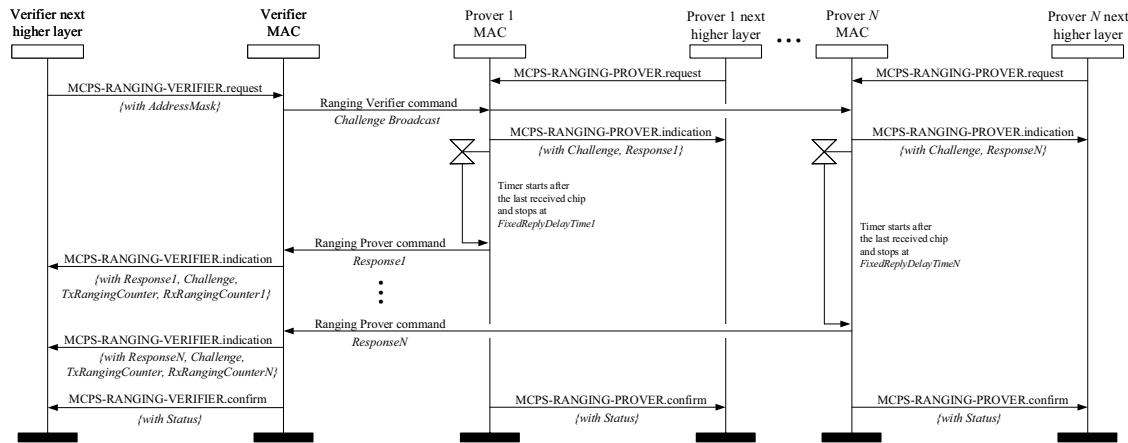


Figure 10-265—Message sequence chart for ACRR based multi-node SS-TWR with one-way authentication

The next higher layer in each prover device should pre-configure the device's fixed reply time referred to in Figure 10-265 as *FixedReplyDelayTime1* to *FixedReplyDelayTimeN* according to a pre-agreed sequence of replying before initiating the MCPS-RANGING-PROVER.request.

For example, using an LRP-ERDEV, the prover device fixed reply delay time can be configured by setting a multiplication factor using the *phyLrpUwbFixedDelayFactor* attribute. The value of the *phyLrpUwbFixedDelayFactor* attribute is multiplied by the value of the *phyLrpUwbFixedReplyTime* attribute to obtain the fixed reply delay time.

The verifier MAC captures each RangingCounter ($1\dots N$) and each Response ($1\dots N$). The prover devices respond to the broadcast address and the verifier uses the AddressMask parameter of the MCPS-RANGING-VERIFIER.request to accept a range of prover addresses. The verifier and prover timeout values, as specified by the TimeOut parameters of the MCPS-RANGING-VERIFIER.request and MCPS-RANGING-PROVER.request primitives, should be set accordingly for the N fixed reply times.

10.33.6 Nested IEs for ACRR

10.33.6.1 Authenticated Challenge-Response Ranging Control IE (ACRRC IE)

The ACRRC IE specifies the supported types of authenticated ranging methods and security levels to be used by the recipient of this IE as part of a challenge-response ranging exchange.

The Content field of the ACRRC IE shall be formatted as shown in Figure 10-266.

Bits: 0–1	2–4	5–7
Authenticated Ranging Method	Security Level	Reserved

Figure 10-266—ACRRC IE Content field format

The Authenticated Ranging Method field defines the ranging method and type of authentication used as specified in Table 10-179.

Table 10-179—Values of the Authenticated Ranging Method field in the ACRRC IE

Authenticated Ranging Method field value	Meaning
0	SS-TWR with one-way authentication.
1	SS-TWR with mutual authentication.
2	DS-TWR with one-way authentication.
3	DS-TWR with mutual authentication.

The Security Level field is set by the originator to instruct the recipient to generate its response according to the security level defined in Table 9-6.

10.33.6.2 ChallengeResponseTransfer IE

The ChallengeResponseTransfer IE conveys challenge or response data between devices performing the ranging as described in 10.33.5.2 and 10.33.5.5. The ChallengeResponseTransfer IE Content field shall be formatted as shown in Figure 10-267.

Bits: 0	1–7	Octets: 4 to 64
Type	Length	Data

Figure 10-267—ChallengeResponseTransfer IE Content field format

The Type field selects the type in the Data field. When Type is zero it indicates that the Data field contains challenge data. When Type is one it indicates that the Data field contains response data.

The Length field is an unsigned integer specifying the number of octets in the Data field, in the range of 4 to 64.

The Data field contains either challenge or response data, depending on the value of the Type field.

10.33.7 MAC commands for ACRR

10.33.7.1 Ranging Verifier command

The Ranging Verifier command is sent by the verifier MAC sublayer as a result of the invocation of an MCPS-RANGING-VERIFIER.request primitive.

The Frame Pending field and the AR field shall be set to zero and the Frame Version field shall set to 0b10.

The Ranging Verifier command Content field shall be formatted as illustrated in Figure 10-268.

Octets: 1	4/8/16/32/64
Reserved	Challenge

Figure 10-268—Ranging Verifier command Content field format

The Reserved field is reserved for future use and shall be set to zero.

The Challenge field contains challenge data of length defined by the SecurityLevel element of the SecurityParams parameter of the MCPS-RANGING-VERIFIER.request primitive, as per Table 10-171.

In the case of the ACRR modes with tolerance of bit errors as described in 10.33.5.3 and 10.33.5.6, the Challenge field contains challenge data of length specified by the ChallengeLength parameter in the MCPS-RANGING-VERIFIER.request primitive. Example challenge lengths are provided in Table 10-172.

The challenge data is a fresh unguessable cryptographic random sequence of octets. The generation of the challenge data should use a cryptographically secure pseudo-random number generator (CSPRNG).

10.33.7.2 Ranging Prover command

The Ranging Prover command is sent by the prover MAC sublayer as a result of the invocation of an MCPS-RANGING-PROVER.request primitive.

The Frame Pending field and the AR field shall be set to zero and the Frame Version field shall set to 0b10.

The Ranging Prover command Content field shall be formatted as illustrated in Figure 10-269.

Octets: 1	4/8/16/32/64
Reserved	Response

Figure 10-269—Ranging Prover command Content field format

The Reserved field is reserved for future use and shall be set to zero.

The Response field contains response data. The response data is created by the MAC sublayer according to the ACRR mode as described in 10.36.2.

In the case of ranging modes with tolerance of bit errors as described in 10.33.5.3 and 10.33.5.6, the response data in the Response field is a fresh unguessable cryptographic random sequence of octets of length specified by the ResponseLength parameter in the MCPS-RANGING-PROVER.request primitive. Example response lengths (same as challenge lengths) are provided in Table 10-172. The generation of the response data should use a cryptographically secure pseudo-random number generator (CSPRNG).

10.33.8 MAC management service primitives for ACRR

10.33.8.1 ACRR verifier primitives

10.33.8.1.1 MCPS-RANGING-VERIFIER.request

The MCPS-RANGING-VERIFIER.request primitive requests the MAC in an ERDEV to initiate an ACRR exchange.

The semantics of this primitive are as follows:

```
MCPS-RANGING-VERIFIER.request (
    TimeOut,
    AcrrMode,
    RawMode,
    ChallengeLength,
    AcricleIncluded,
    AddressMask,
    SrcAddrMode,
    DstAddrMode,
    DstPanId,
    DstAddr,
    SecurityParams,
    DistanceCommitmentLevel,
    UwbPreambleSymbolRepetitions,
    DataRate,
    LocationEnhancingInformationPostamble,
    LocationEnhancingInformationPostambleLength,
    PanIdSuppressed,
    SeqNumSupressed
)
```

The primitive parameters are defined in Table 10-180.

Table 10-180—MCPS-RANGING-VERIFIER.request parameters

Name	Type	Valid range	Description
TimeOut	Integer	0x00000000–0xffffffff	Maximum time period for the activation of the challenge-response ranging exchange. The time out period is defined by: $\text{TimeOut} \times \text{phyLrpUwbFixedReplyTime}$.
AcrrMode	Integer	0–3	Selects the ACRR mode as specified Table 10-179.
RawMode	Boolean	TRUE, FALSE	If TRUE, the FCS check is ignored and the received frame is always passed to the next higher layer. If FALSE, the FCS check is active.
ChallengeLength	Integer	As per 10.33.7.1	Specifies the length in octets of the challenge to be used by the MAC sublayer when RawMode is set to TRUE.

Table 10-180—MCPS-RANGING-VERIFIER.request parameters (continued)

Name	Type	Valid range	Description
AcrrcIEIncluded	Boolean	TRUE, FALSE	If TRUE, the MAC sublayer generates an ACRRRC IE and transmits it within the MAC Command frame. The content of the ACRRRC IE shall correspond to the values indicated in the AcrMode and SecurityParams parameters.
AddressMask	—	As specified by the SrcAddrMode parameter	The address mask bits enable the corresponding address bit check when set to one. When set to zero the corresponding address bit is don't care.
SrcAddrMode	Enumeration	NONE, SHORT, EXTENDED	The source addressing mode.
DstAddrMode	Enumeration	NONE, SHORT, EXTENDED	The destination addressing mode.
DstPanId	Integer	0x0000–0xffff	The PAN ID of the entity to which the command is being transferred.
DstAddr	—	As specified by the DstAddrMode parameter	The address of the entity to which the command is being transferred.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.
DistanceCommitmentLevel	Enumeration	DCL_1_4096, DCL_1_2048, DCL_1_1024, DCL_1_512, DCL_1_256, DCL_1_128, DCL_1_64, DCL_DISABLED	Specifies the aperture time $T_{int,RF}$ as a fraction of an RSTU as per the definition in 11.3.2.
UwbPreambleSymbolRepetitions	Integer	0, 16, 32, 64, 128, 256, 512, 1024, 4096, 8192	The PSR of the LRP UWB frame. A zero value is used for all other PHYs.
DataRate	Integer	—	Indicates the data rate. For LRP UWB PHYs, valid values are defined in Table 19-1. For all other PHYs, the parameter is set to zero.
LocationEnhancingInformationPostamble	Enumeration	As defined in Table 8-30	As defined in Table 8-30.
LocationEnhancingInformationPostambleLength	Enumeration	As defined in Table 8-30	As defined in Table 8-30.
PanIdSuppressed	Boolean	TRUE, FALSE	Set to TRUE if the PAN ID is suppressed in the frame; FALSE otherwise.
SeqNumSuppressed	Boolean	TRUE, FALSE	Set to TRUE if the sequence number is suppressed in the frame; FALSE otherwise.

Upon receipt of the MCPS-RANGING-VERIFIER.request primitive, the MAC sublayer is enabled with a set of selected parameters including a timeout, the ACRR mode, enabling or disabling the FCS checking (RawMode), distance commitment level, and the other parameters as defined in Table 10-180. Setting these parameters depends on the ACRR mode and it is described in 10.33.5 for each mode.

After the request, the verifier MAC sublayer generates a fresh unguessable cryptographic random number. The generation should use a cryptographically secure pseudo-random number generator (CSPRNG). The Ranging Verifier command (as defined in 10.33.7.1) containing this number in the challenge data is then transmitted, and the receiver is enabled to await the response.

In multi-node ranging with broadcast address, an AddressMask is configured to filter addresses from the prover responses, and the TimeOut parameter determines how long the verifier waits for prover command responses before ending the ranging exchange and issuing the MCPS-RANGING-VERIFIER.confirm.

If the TimeOut timer expires and no Ranging Prover commands have been received, ranging will be aborted and the MCPS-RANGING-VERIFIER.confirm primitive will be generated with a Status parameter value of TRANSACTION_EXPIRED; if at least one Ranging Prover command has been received prior to the timer expiration, the MCPS-RANGING-VERIFIER.confirm primitive will be generated with a Status parameter value of SUCCESS. When the DestAddr parameter is set to the broadcast address, multi-node is assumed.

10.33.8.1.2 MCPS-RANGING-VERIFIER.confirm

The MCPS-RANGING-VERIFIER.confirm primitive reports the result of an MCPS-RANGING-VERIFIER.request.

The semantics of this primitive are as follows:

```
MCPS-RANGING-VERIFIER.confirm (
    Status
)
```

The primitive parameters are defined in Table 10-181.

Table 10-181—MCPS-RANGING-VERIFIER.confirm parameters

Name	Type	Valid range	Description
Status	Enumeration	SUCCESS, TRANSACTION_EXPIRED, INVALID_PARAMETER, RANGING_VERIFIER_NOT_SUPPORTED	The result of the request for the ranging operation.

The MCPS-RANGING-VERIFIER.confirm primitive is generated by the MAC sublayer at the verifier device and issued to the next higher layer after the ranging operation has finished either by receiving a Ranging Prover command and issuing an MCPS-RANGING-VERIFIER.indication primitive or when a timeout has occurred as shown in Figure 10-257 and Figure 10-258.

10.33.8.1.3 MCPS-RANGING-VERIFIER.indication

The MCPS-RANGING-VERIFIER.indication primitive indicates the reception of the Ranging Prover command from a prover device as part of a challenge-response ranging exchange.

The semantics of this primitive are as follows:

```
MCPS-RANGING-VERIFIER.indication (
    SrcAddrMode,
    SrcPanId,
    DstAddrMode,
    DstPanId,
    DstAddr,
    HeaderList,
    PayloadList,
    SecurityParams,
    RangingStatus,
    RangingSecurityParams,
    RangingReportDescriptor,
    Rssi,
    RangingChallenge,
    RangingResponse
)
```

The primitive parameters are defined in Table 10-182.

Table 10-182—MCPS-RANGING-VERIFIER.indication parameters

Name	Type	Valid range	Description
SrcAddrMode	Enumeration	NONE, SHORT, EXTENDED	The source addressing mode of the received command.
SrcPanId	Integer	0x0000–0xffff	The PAN ID of the entity from which the command was received. Valid only when a source PAN ID is included in the received frame.
DstAddrMode	Enumeration	NONE, SHORT, EXTENDED	The destination addressing mode of the received command.
DstPanId	Integer	0x0000–0xffff	The PAN ID of the entity to which the command is being transferred. Set to the receiver's PAN ID if the PAN ID is not carried in the received command.
DstAddr	—	As specified by the DstAddrMode parameter	The address of the entity to which the command is being transferred.
HeaderList	As per Table 8-32	As defined in Table 8-32	As defined in Table 8-32.
PayloadList	As per Table 8-32	As defined in Table 8-32	As defined in Table 8-32.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.
RangingStatus	Enumeration	RANGING_ACTIVE, RANGING_ABORTED, NO_RANGING_RECEIVED	A value of NO_RANGING_RECEIVED indicates that the received frame was not a ranging frame. A value of RANGING_ACTIVE denotes ranging is active and enabled. A value of RANGING_ABORTED denotes that ranging was disabled or timed out.

Table 10-182—MCPS-RANGING-VERIFIER.indication parameters (continued)

Name	Type	Valid range	Description
RangingSecurityParams	Structure	As defined in Table 8-2	Provides the security level, (as defined in Table 9-6), used by the MAC security services during the ranging exchange when an ACRRRC IE is used. As defined in Table 8-2.
RangingReportDescriptor	Structure	As defined in Table 8-28	Reports ranging related results.
Rssi	Integer	0x00–0xff	The Received Signal Strength Indicator is a measure of the RF power level at the input of the transceiver measured during the SFD.
RangingChallenge	Set of octets	As defined in 10.33.7.1	Payload sent by the verifier with RangingVerifier command.
RangingResponse	Set of octets	As defined in 10.33.7.2	Payload sent by the prover with RangingProver command.

The MCPS-RANGING-VERIFIER.indication primitive is generated by the MAC sublayer at the verifier device and issued to the next higher layer upon receipt of a Ranging Prover command. This primitive provides the received RangingResponse from the prover device and the transmitted RangingChallenge from the verifier device together with the RxRangingCounter value and the RangingStatus as described in Table 10-182.

10.33.8.2 ACRR prover primitives

10.33.8.2.1 MCPS-RANGING-PROVER.request

The MCPS-RANGING-PROVER.request primitive prepares the MAC in an ERDEV to receive a challenge in an ACRR exchange, and to respond accordingly.

The semantics of this primitive are as follows:

```
MCPS-RANGING-PROVER.request ( 
    TimeOut,
    AcrrMode,
    RawMode,
    ResponseLength,
    AcrrcleIncluded,
    SrcAddrMode,
    DstAddrMode,
    DstPanId,
    DstAddr,
    SecurityParams,
    DistanceCommitmentLevel,
    UwbPreambleSymbolRepetitions,
    DataRate,
    LocationEnhancingInformationPostamble,
    LocationEnhancingInformationPostambleLength,
    PanIdSuppressed,
    SeqNumSupressed
)
```

The primitive parameters are defined in Table 10-183.

Table 10-183—MCPS-RANGING-PROVER.request parameters

Name	Type	Valid range	Description
TimeOut	Integer	0x000000–0xffffffff	Maximum time period for the activation of the challenge-response ranging exchange. When the timeout period expires or the MCPS-RANGING-PROVER.confirm is received, the current ranging transfer will be aborted and ranging disabled. The time out period is defined by: $\text{TimeOut} \times \text{phyLrpUwbFixedReplyTime}$.
AcrrMode	Integer	0–3	Selects the ACRR mode as specified Table 10-179.
RawMode	Boolean	TRUE, FALSE	If TRUE, the FCS check is ignored and the received frame is always passed to the next higher layer. If FALSE, the FCS check is active.
ResponseLength	Integer	As per 10.33.7.2	Specifies the length in octets of the response to be used by the MAC sublayer when RawMode is set to TRUE.
AcrccleIncluded	Boolean	TRUE, FALSE	If TRUE, the MAC sublayer generates an ACRRCC IE and transmits it within the MAC Command frame. The content of the ACRRCC IE shall correspond to the values indicated in the AcrrMode and SecurityParams parameters.
SrcAddrMode	Enumeration	NONE, SHORT, EXTENDED	The source addressing mode.

Table 10-183—MCPS-RANGING-PROVER.request parameters (continued)

Name	Type	Valid range	Description
DstAddrMode	Enumeration	NONE, SHORT, EXTENDED	The destination addressing mode.
DstPanId	Integer	0x0000–0xffff	The PAN ID of the entity to which the command is being transferred.
DstAddr	—	As specified by the DstAddrMode parameter	The address of the entity to which the command is being transferred.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.
DistanceCommitmentLevel	Enumeration	As defined in Table 10-180	As defined in Table 10-180.
UwbPreambleSymbolRepetitions	Integer	As defined in Table 8-30	As defined in Table 8-30.
DataRate	Integer	—	Indicates the data rate. For LRP UWB PHYs, valid values are defined in Table 19-1. For all other PHYs, the parameter is set to zero.
LocationEnhancingInformationPostamble	Enumeration	As defined in Table 8-30	As defined in Table 8-30.
LocationEnhancingInformationPostambleLength	Enumeration	As defined in Table 8-30	As defined in Table 8-30.
PanIdSuppressed	Boolean	TRUE, FALSE	Set to TRUE if the PAN ID is suppressed in the frame; FALSE otherwise.
SeqNumSuppressed	Boolean	TRUE, FALSE	Set to TRUE if the sequence number is suppressed in the frame; FALSE otherwise.

Upon receipt of the MCPS-RANGING-PROVER.request primitive, the MAC sublayer enables the receiver to receive the challenge and process it according to the set parameters including a timeout, the ACRR mode, enabling or disabling the FCS checking (RawMode), setting the response length (for RawMode), the distance commitment level, and the other parameters as defined in Table 10-183. The choice of parameter values depends on the ACRR mode as described in 10.33.5 for each mode.

When a Ranging Verifier command is received, the response data is created by the prover MAC sublayer, according to the selected ACRR mode and security level, and sent using the Ranging Prover command (as defined in 10.33.7.2).

In multi-node ranging the prover replies to the broadcast address as described in 10.33.5.8.

If the Timeout timer expires, ranging will be aborted and the MCPS-RANGING-PROVER.confirm primitive will be issued with a Status parameter value of TRANSACTION_EXPIRED.

10.33.8.2.2 MCPS-RANGING-PROVER.confirm

The MCPS-RANGING-PROVER.confirm primitive reports the result of an MCPS-RANGING-PROVER.request.

The semantics of this primitive are as follows:

```
MCPS-RANGING-PROVER.confirm (
    Status
)
```

The primitive parameters are defined in Table 10-184.

Table 10-184—MCPS-RANGING-PROVER.confirm parameters

Name	Type	Valid range	Description
Status	Enumeration	SUCCESS, TRANSACTION_EXPIRED, INVALID_PARAMETER, RANGING_PROVER_NOT_SUPPORTED	The result of the request for the ranging operation.

The MCPS-RANGING-PROVER.confirm primitive is generated by the MAC sublayer at the prover device and issued to the next higher layer after the ranging operation has finished either by issuing an MCPS-RANGING-VERIFIER.indication primitive and expiration of the fixed reply time timer or when a timeout has occurred as shown in Figure 10-257.

10.33.8.2.3 MCPS-RANGING-PROVER.indication

The MCPS-RANGING-PROVER.indication primitive indicates the reception of the Ranging Verifier command from a verifier device as part of a challenge-response ranging exchange.

The semantics of this primitive are as follows:

```
MCPS-RANGING-PROVER.indication (
    SrcAddrMode,
    SrcPanId,
    SrcAddr,
    DstAddrMode,
    DstPanId,
    DstAddr,
    HeaderList,
    PayloadList,
    SecurityParams,
    RangingReportDescriptor,
    Rssi,
    RangingSecurityParams,
    RangingChallenge,
    RangingResponse
)
```

The primitive parameters are defined in Table 10-185.

The MCPS-RANGING-PROVER.indication primitive is generated by the MAC sublayer at the prover device and issued to the next higher layer upon receipt of a Ranging Verifier command. The primitive will provide the received challenge from the verifier device and the generated response from the prover device to the next higher layer as listed in Table 10-185.

Table 10-185—MCPS-RANGING-PROVER.indication parameters

Name	Type	Valid range	Description
SrcAddrMode	Enumeration	NONE, SHORT, EXTENDED	The source addressing mode of the received command.
SrcPanId	Integer	0x0000–0xffff	The PAN ID of the entity from which the command was received. Valid only when a source PAN ID is included in the received frame.
SrcAddr	—	As specified by the SrcAddrMode parameter	The source address of the command that was received. Valid only when the source address is included in the received frame.
DstAddrMode	Enumeration	NONE, SHORT, EXTENDED	The destination addressing mode of the received command.
DstPanId	Integer	0x0000–0xffff	The PAN ID of the entity to which the command is being transferred. Set to the receiver's PAN ID if the PAN ID is not carried in the received frame.
DstAddr	—	As specified by the DstAddrMode parameter	The address of the entity to which the command is being transferred.
HeaderIeList	As per Table 8-32	As defined in Table 8-32	As defined in Table 8-32.
PayloadIeList	As per Table 8-32	As defined in Table 8-32	As defined in Table 8-32.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.
RangingReportDescriptor	Structure	As defined in Table 8-28	Reports ranging related results.
Rssi	Integer	0x00–0xff	The Received Signal Strength Indicator is a measure of the RF power level at the input of the transceiver measured during the SFD.
RangingSecurityParams	Structure	As defined in Table 10-182	As defined in Table 10-182.
RangingChallenge	Set of octets	As defined in 10.33.7.1	Payload sent by the verifier with Ranging Verifier command.
RangingResponse	Set of octets	As defined in 10.33.7.2	Payload sent by the prover with Ranging Prover command.

10.34 Ranging: Ranging message non-receipt exchange

10.34.1 Overview

A Data frame can be used to convey the non-receipt of messages during a ranging round. This procedure can be used whenever ERDEVs are scheduled to send messages bearing payload to the controller. As depicted in Figure 10-270, the RCM is received successfully by both responders, however Responder-2 does not receive the expected ranging initiation message. Rather than remaining idle in its assigned time slot, Responder-2 can send a message with the Ranging Message Non-Receipt IE (RMNR IE), defined in 10.34.2.1, to indicate its failure to receive the ranging initiation message, and implicitly confirm its receipt of the RCM. Once the

controller receives the ranging response message from Responder-1, the controller also knows that the RCM has been received by Responder-1.

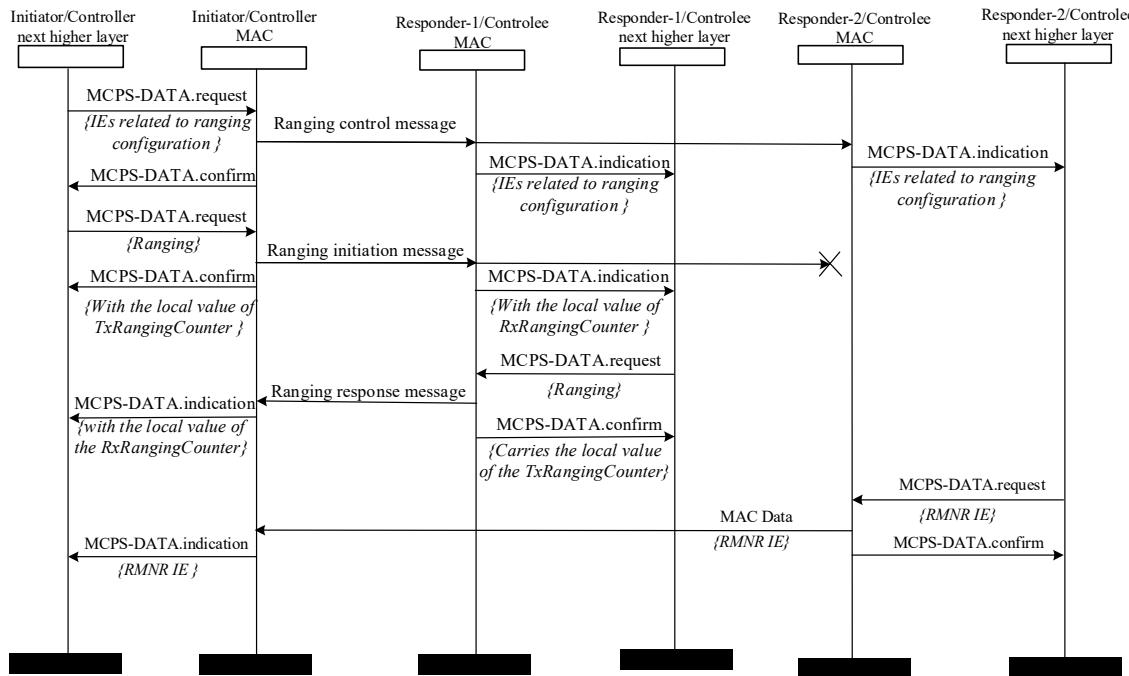


Figure 10-270—Ranging message non-receipt exchange for one initiator and multiple responders: controller is a ranging initiator

10.34.2 Nested IEs for ranging message non-receipt exchange

10.34.2.1 Ranging Message Non Receipt IE (RMNR IE)

The RMNR IE may be used to indicate the non-receipt of an expected ranging message. This IE is formatted without any Content field. The use of the RMNR IE is described in 10.34.

10.35 Ranging ancillary information

10.35.1 Overview

A ranging block may have one or more ranging rounds during which ranging ancillary information can be exchanged between initiators and responders. For ranging ancillary information exchange, the following terminology is used:

- Initiator: A ranging device that sends ranging ancillary information.
- Responder: A ranging device that receives ranging ancillary information.

In the current ranging round and any subsequent number of ranging round(s) following the RCM the information exchange can be scheduling-based or contention-based. Note that the number of ranging rounds controlled by this RCM is indicated by the Ranging Validity Rounds field of the ARC IE (described in 10.32.9.1). The next higher layer can use the fields of the Ranging Ancillary Information Message Counter and Type IE (RAICT IE), as described in 10.35.2.1, to transmit information over multiple MAC messages spanning multiple ranging slots in a ranging round and for managing retransmissions. The next higher layer may use the Ranging Or Ancillary Message Number field of the RAICT IE to keep track of multiple

messages. If the initiator is not the controller, the RAICT IE can be used to request, using the Request field, from the controller that the number of slots as specified by the Frames Remaining field be scheduled for the next exchange.

10.35.2 Nested IEs for ranging ancillary information

10.35.2.1 Ranging Ancillary Information Message Counter and Type IE (RAICT IE)

The RAICT IE is used during ranging ancillary information exchange. The Content field of the RAICT IE shall be formatted as shown in Figure 10-271.

Bits: 0	1	2–7	Octets: 0/1	0/1
Request	Ranging Or Ancillary Message Number Present	Reserved	Ranging Or Ancillary Message Number	Frames Remaining

Figure 10-271—RAICT IE Content field format

The Request field when one indicates that this RAICT IE is used to request the slots from the controller. Otherwise it is set to zero.

The Ranging Or Ancillary Message Number Present field when one indicates that the Ranging Or Ancillary Message Number field is present in this IE, or when zero that the field is not included.

The Ranging Or Ancillary Message Number field conveys the ranging or ancillary message number.

The Frames Remaining field conveys to the responder the number of frames remaining to complete the present ranging or ancillary data message exchange, or, when the Request field is one, to convey to the controller a request to schedule this number of slots for the next exchange.

The initiator may use the RAICT IE in two different ways:

- When the Request field is zero, to convey the sequence number of the current Data frame, the number of ranging ancillary Data frames remaining to complete this message, and the message type to the responder.
- When the Request field is one, to request the controller to schedule the number of slots as specified in the Frames Remaining field.

10.36 Ranging: Multiple message receipt confirmation

10.36.1 Overview

A multiple message receipt confirmation message (MMRCM) is a frame containing a Ranging Multiple Message Receipt Confirmation IE (RMMRC IE). A responder may use an MMRCM to confirm the receipt of multiple messages originating from the same initiator or to confirm the receipt of multiple messages originating from multiple initiators. The Ranging Multiple Message Receipt Confirmation IE (RMMRC IE), described in 10.36.2.1, may be used by the responder (or recipient of multiple messages) to acknowledge the multiple messages. The Multiple Message Receipt Confirmation Request (MMRCR) field of the ARC IE is used to request the receipt confirmation from the recipient devices.

Figure 10-272 illustrates an example message sequence chart for MMRCM with MMRCR field in the ARC IE from controller in the RCM. Devices A_1 to A_N each send multiple messages to devices B_1 to B_M , where the Message i_{A_j} is the i th message transmitted from A_j for j in 1 to N . Device A_i transmits K_{Ai} messages. Upon the completion of onward messages from devices A_1 to A_N , devices B_1 to B_M confirm the receipt of all the messages to different initiators by sending MMRCM via multicast or multi-node messages using the Ranging Multiple Message Receipt Confirmation IE (RMMRC IE). The messages and the MMRCM slots can be scheduled or can be contention-based or can be a combination of both. The Address field and the MMRC bitmap field in the MMRC List element of the RMMRC IE are used to indicate the source of the received message in the corresponding slots.

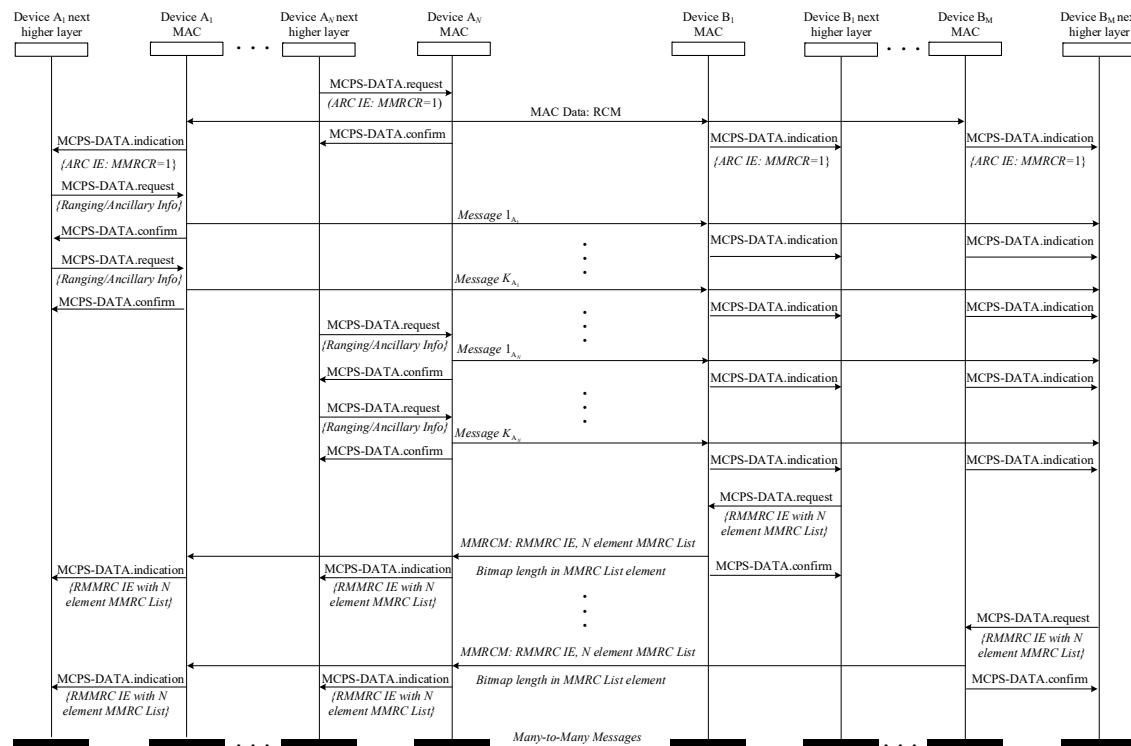


Figure 10-272—Message sequence chart showing example use of MMRCM

10.36.2 Nested IEs for ranging ancillary information

10.36.2.1 Ranging Multiple Message Receipt Confirmation IE (RMMRC IE)

The receipt of messages from one or more initiators can be confirmed using the RMMRC IE. A bitmap and the initiator address are used to convey the confirmation of the receipt of messages from an initiator. The Content field of the RMMRC IE shall be formatted as shown in Figure 10-273.

Bits: 0	1	2–7	Octets: 1	variable
Address Present	Address Size	Reserved	MMRC List Length	MMRC List

Figure 10-273—RMMRC IE Content field format

The Address Present field when one indicates that an Address field is present in each element of the MMRC List, or when zero indicates that the Address field is not present.

The Address Size field is valid when the Address Present field is one and is not used and ignored upon receipt, when the Address Present field is zero. The Address Size field value of zero indicates that short addresses are used in MMRC List field, and value one indicates that extended addresses are used.

The MMRC List Length field indicates the number of elements in the MMRC List field each of which is formatted as per Figure 10-274.

Octets: 0/2/8	1	variable
Address	MMRC Bitmap Length	MMRC Bitmap

Figure 10-274—MMRC List element format

The Address field when present indicates the address of the initiator for which the MMRC Bitmap field of the corresponding list element indicates the receipt confirmation.

The MMRC Bitmap Length field is given by ceiling of ((Number of slots being acknowledged)/8).

The MMRC Bitmap field contains a binary bitmap string. Each bit maps to the slots in the ranging round(s) for which the RMMRC IE is used to send message receipt confirmations. Each bit confirms the receipt of a message in the slot. The bit is set to one to confirm successful reception, otherwise it is set to zero to convey that the message was not received or not addressed to the MMRC sender in that slot. The first bit in time sent in the field refers to the first time slot and the subsequent bits refer chronologically to the subsequent time slots. When the number of bits sent in the MMRC bitmap is greater than the number of slots for which the receipt confirmation is being used, the last bits sent, given by Extra bits = (Number of bits in MMRC bitmap – Number of slots for receipt confirmation), are discarded.

10.37 Timeslot relaying based link extension (TRLE)

10.37.1 General

In a star topology, the range of the network is limited by the transmission and reception range of the devices forming a link. There are occasions when a further range extension of the network may be required. An example would be when supporting a very sparse dispersion of devices beyond the radio range of a PAN coordinator to an end device. Another example may arise when maintaining connection with an end device where the RF environment degrades as a result of geographic change after the initial deployment.

A PAN relay is a coordinator that relays MAC frames either in the direction of the PAN coordinator or in the direction of a device. This subclause provides specific MAC capabilities for extending the range of a link in a star network composed of the PANs using superframe structure or the DSME-enabled devices. The TRLE PAN relays residing between the PAN coordinator and devices support transparent link connectivity without additional networking overheads to an end device.

Some of the capabilities provided by this feature are as follows:

- Frame filtering in relaying mode
- Frame relaying on a link between the coordinator and devices in a PAN using superframe structure
- Management of multihop relaying path between the TRLE-enabled PAN coordinator and devices
- Frame relaying on a TRLE multihop path

10.37.2 Link extension for a PAN using superframe structure

The TRLE PAN relay extends the link of a PAN using superframe structure by relaying frames at the MAC sublayer in the direction to a device (i.e., outward relaying) or in the direction to the PAN coordinator (i.e., inward relaying).

The TRLE PAN relay provides a one-hop relaying link extension for PANs using superframe structure. The TRLE-enabled PAN coordinator and the TRLE PAN relays provide multihop relaying link extension for the DSME-enabled PAN.

The TRLE PAN relay may be used in several PANs using superframe structure configurations, as shown in Figure 10-275: (a) PAN coordinator using superframes - TRLE PAN relay - non-TRLE device, (b) TRLE-enabled PAN coordinator - multiple TRLE PAN relays - DSME-enabled device or TRLE-enabled device.

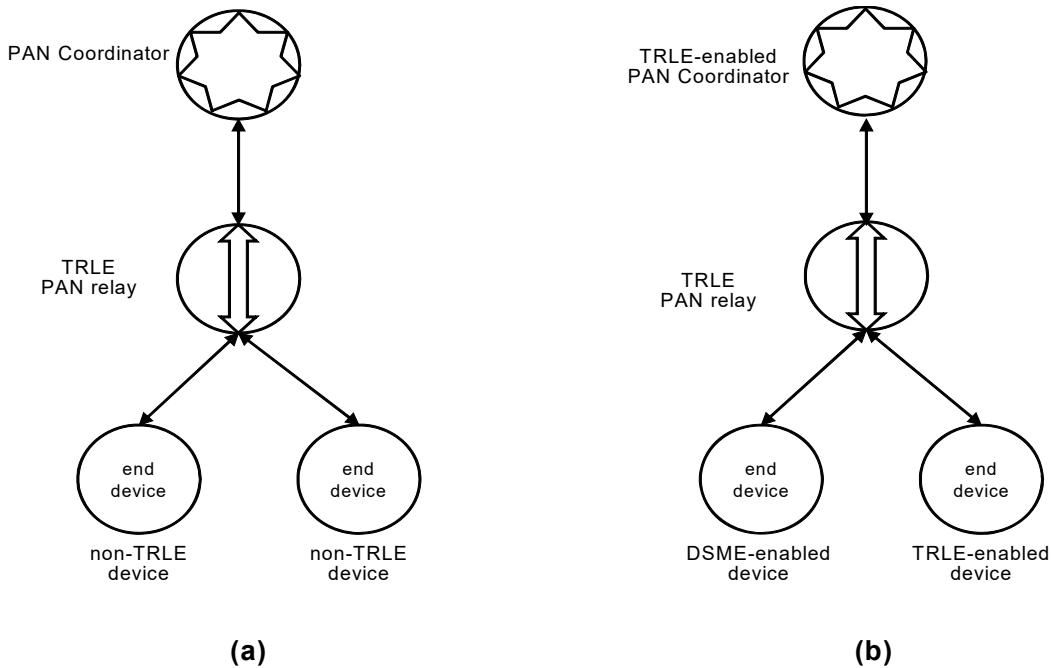


Figure 10-275—Usage of the TRLE PAN relay

10.37.3 Link extension for the non-TRLE PAN

10.37.3.1 TRLE PAN relay association and disassociation

A device shall perform as a TRLE PAN relay if the PIB attributes *macTrleEnabled* and *macTrleRelayingMode* are set to TRUE. A TRLE PAN relay shall associate as a coordinator with the PAN using superframe structure, as described in 10.21.2.

After completing association, the next higher layer may initiate relaying frames at the MAC sublayer by issuing the MLME-TRLE-MANAGEMENT.request primitive with the ManagementType parameter set to RELAY_ON, as described in 10.37.5.3.1, so that the MLME shall configure *macSyncRelayingOffset* to be set equal to the SyncRelayingOffset parameter of the MLME-TRLE-MANAGEMENT.request primitive.

The MAC sublayer of the TRLE PAN relay shall begin relaying frames, as described in 10.37.3.3. The next higher layer shall be notified of the result of initiating the TRLE PAN relay through the MLME-TRLE-

MANAGEMENT.confirm primitive with ManagementType parameter set to RELAY_ON and Status parameter, as described in 10.37.5.3.4.

If the TRLE PAN relay wants to leave the PAN, the next higher layer may halt the relaying by issuing the MLME-TRLE-MANAGEMENT.request primitive with the ManagementType parameter set to RELAY_OFF, as described in 10.37.5.3.1. The next higher layer shall be notified of the result of halting the TRLE PAN relay through the MLME-TRLE-MANAGEMENT.confirm primitive with ManagementType parameter set to RELAY_OFF and Status parameter, as described in 10.37.5.3.4.

After halting the relaying, the TRLE PAN relay shall disassociate with the PAN using superframe structure, as described in 10.21.3.

10.37.3.2 Frame filtering in relaying mode

In relaying mode (i.e., *macTrleRelayingMode* set to TRUE), the MAC sublayer shall maintain the first level of filtering and the second level of filtering described in 6.6.2 and accept only frames that satisfy all of the third level filtering requirements except matching of a destination address.

If the frame is valid, the MAC sublayer either passes the frame to the next higher layer or relays the frame onward according to the destination address. The frame having its destination addresses as the broadcast address shall be passed to the next higher layer and be also relayed onward.

10.37.3.3 One-hop relaying

The TRLE PAN relay for a PAN using superframe structure or the DSME-enabled PAN provides one-hop relaying to extend the range of the link.

If a short destination address included in the frame matches *macShortAddress*, or if an extended destination address included in the frame matches *macExtendedAddress*, the frame shall be handled as described in 6.6.2.

A frame with a destination address equal to the broadcast address shall be handled as described in 6.6.2 and shall also be relayed by the MAC sublayer.

If a short destination address included in the frame does not match *macShortAddress*, or if an extended destination address included in the frame does not match *macExtendedAddress*, the frame shall be relayed by the MAC sublayer.

Frames received from the PAN coordinator shall be relayed after delaying $\text{superframe duration} \times \text{macSynchRelayingOffset}$, and frames received from the device shall be relayed after delaying $\text{superframe duration} \times [2^{(BO-SO)} - \text{macSynchRelayingOffset}]$, as shown in Figure 10-276. The delay for relaying is determined by the TRLE PAN relay, when associating with the PAN using superframe structure. The algorithm for choosing *macSynchRelayingOffset* is outside the scope of this standard.

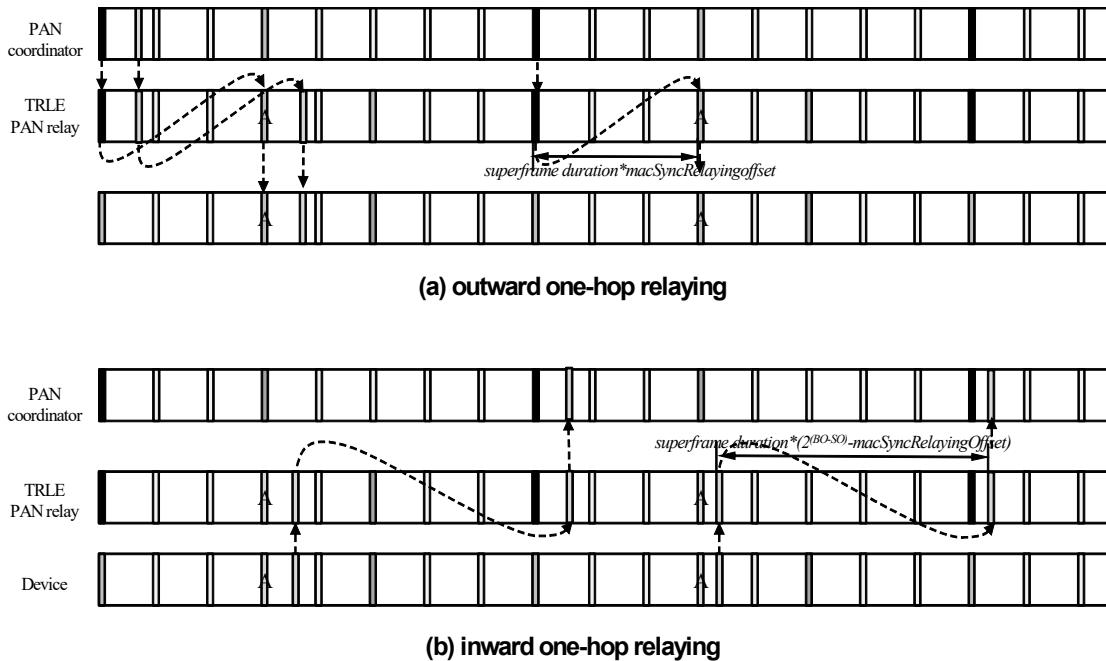


Figure 10-276—Relaying frames for the coordinator using superframe structure and a device

10.37.4 Link extension for the TRLE-enabled PAN

10.37.4.1 TRLE-enabled PAN

The PAN coordinator of a DSME-enabled PAN shall perform as a TRLE-enabled PAN coordinator, if the PIB attribute *macTrleEnabled* is set to TRUE. The TRLE-enabled PAN coordinator may provide a multihop relaying path with the TRLE PAN relays.

Beacon frames from the TRLE-enabled PAN coordinator are received by the PAN relays within the transmission range of the PAN coordinator from tier 1 of the TRLE-enabled PAN. The PAN relays that are within a transmission range of the tier 1 PAN relays, but not within PAN coordinator range, form tier 2 of the TRLE-enabled PAN, and so on, as illustrated in Figure 10-277. For any given PAN relay, a neighboring PAN relay closer to the PAN coordinator is called an inner PAN relay and a PAN relay closer to the end device is called an outer PAN relay. The relaying of a TRLE-enabled PAN is limited to seven tiers.

The TRLE-enabled PAN coordinator and the PAN relay use a cyclic-superframe structure. The cyclic-superframe structure is based on the DSME multi-superframe structure, as illustrated in Figure 10-278.

The CAP is divided into timeslots for transmitting a frame to the PAN coordinator (i.e., the prioritized device timeslot) and timeslots for transmitting a frame to end devices (i.e., the coordinator timeslot). The prioritized device timeslot starts after the beacon and continues for a preset number of timeslots, *macNumPrioritizedDeviceSlot*. The coordinator timeslot starts after the prioritized device timeslot and continues for a preset number of timeslots, *macNumCoordSlot*.

The timeslot in CFP is bidirectional (i.e., the bidirectional device timeslot). The bidirectional device timeslots for a TRLE PAN relay or TRLE-enabled device may be pre-assigned or allocated before use.

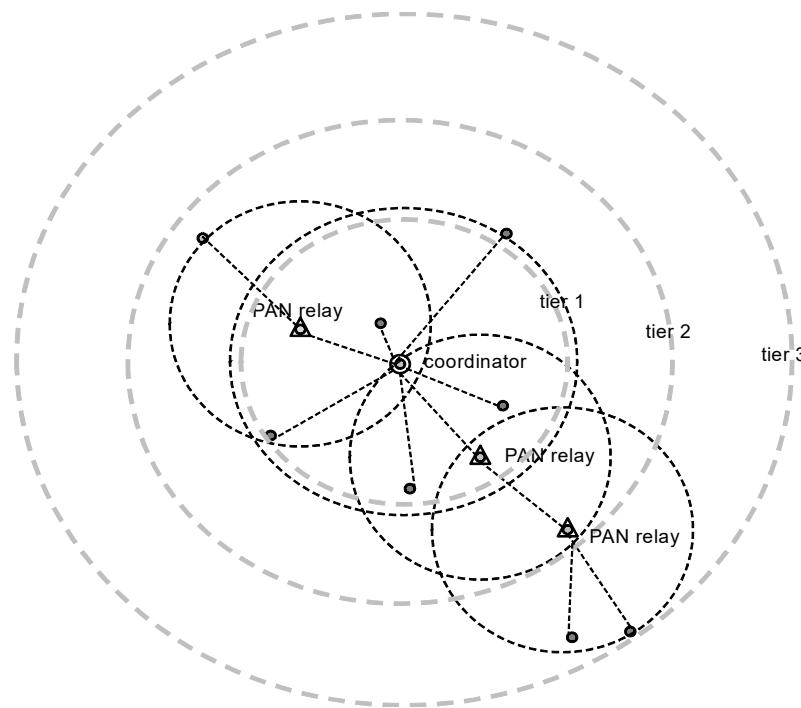


Figure 10-277—Hierarchy of relaying in the TRLE-enabled PAN

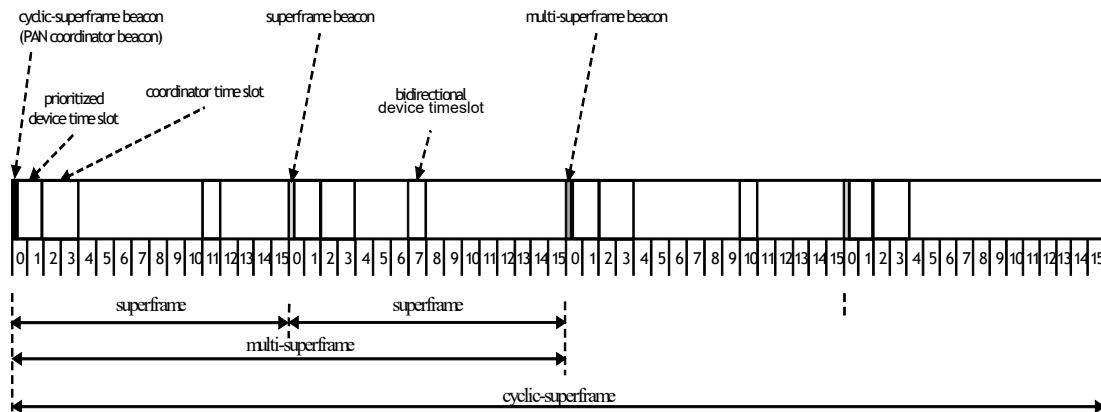


Figure 10-278—Timeslots in a TRLE cyclic-superframe

10.37.4.2 Starting a TRLE-enabled PAN

A PAN coordinator with PIB attributes *macDsmeEnabled* and *macTrleEnabled* set to TRUE shall start a DSME-enabled PAN by following the procedure described in 6.4.2.2.

The PAN coordinator shall be instructed to begin operating as the TRLE-enabled PAN coordinator through the use of the MLME-TRLE-MANAGEMENT.request primitive, as described in 10.37.5.3.1, with the ManagementType parameter set to START.

On receipt of this primitive, the MLME configures the following MAC PIB attributes:

- *macNumPrioritizedDevice* shall be set equal to the NumPrioritizedDevice parameter of the MLME-TRLE-MANAGEMENT.request primitive.
- *macNumCoordSlot* shall be set equal to the NumCoordSlot parameter of the MLME-TRLE-MANAGEMENT.request primitive.

After completing this, the MAC sublayer shall issue the MLME-TRLE-MANAGEMENT.confirm primitive with the ManagementType parameter set to START and a status of SUCCESS, as described in 10.37.5.3.4, and begin operating as the TRLE-enabled PAN coordinator.

The TRLE-enabled PAN is formed when the TRLE-enabled PAN coordinator advertises the presence of the TRLE-enabled PAN by sending an enhanced beacon, which contains the DSME PAN Descriptor IE and the TRLE Descriptor IE, as defined in 10.37.5.1.1.

10.37.4.3 TRLE relaying path formation

The next higher layer of a TRLE PAN relay or TRLE-enabled device shall perform a MAC sublayer reset, by issuing the MLME-RESET.request primitive with the SetDefaultPib parameter set to TRUE, and then complete either an active or a passive channel scan, as defined in 6.4.1.2. The results of the channel scan should be used to choose a suitable PAN and to select an inner coordinator, either the TRLE-enabled PAN coordinator or an inner TRLE PAN relay, through which it will attempt to associate.

Following the selection of a TRLE-enabled PAN, a TRLE PAN relay or a TRLE-enabled device shall be instructed to associate with a DSME-enabled PAN, as described in 10.21.2.

After completing association, the next higher layer may instruct through the MLME-TRLE-MANAGEMENT.request primitive with the ManagementType parameter set to JOIN and the TxGrade parameter set to GRADE_0 for the TRLE PAN relay or set to GRADE_2 for the TRLE-enabled device, as described in 10.37.5.3.1, that the MLME configures the following MAC PIB attributes:

- *macRelayingTier* shall be set equal to the SrcRelayingTier parameter of the MLME-TRLE-MANAGEMENT.request primitive.
- *macInnerRelayingOffset* shall be set equal to the InnerRelayingOffset parameter of the MLME-TRLE-MANAGEMENT.request primitive.
- *macNumBidirectionalDeviceSlot* shall be set equal to the NumBidirectionalDeviceSlot parameter of the MLME-TRLE-MANAGEMENT.request primitive.

The MAC sublayer shall initiate the joining procedure by sending a TRLE Management Request command with the Management Type field set to Join, as described in 10.37.5.2.1. The TRLE Descriptor IE shall be included in the Header IE field of the TRLE Management Request command. The TxGrade parameter of the request primitive is set to the Grade of Link Access field of the TRLE Descriptor IE. The timeslot in which the TRLE Management Request command will be transmitted shall be selected by the InnerRelayingOffset parameter.

When relaying a TRLE Management Request command with the Management Type field set to Join, the PAN relay collects a source address of the MHR field and the PAN Relay Address field of the TRLE Descriptor IE of the frame relayed, and updates the *macPanRelayList*.

The TRLE-enabled PAN coordinator indicates the reception of a TRLE Management Request command through the MLME-TRLE-MANAGEMENT.indication primitive with the ManagementType parameter set to JOIN, as described in 10.37.5.3.2. The Grade of Link Access field of the TRLE Descriptor IE is set to the TxGrade parameter of the indication primitive.

The next higher layer of the TRLE-enabled PAN coordinator shall assign timeslots in a cyclic-superframe for the bidirectional device slot and determine the relaying delay at the TRLE PAN relay requesting the TRLE path formation with information provided by the BeaconBitmap parameter and RelyingPathList parameter of indication primitive. The algorithm for choosing the relaying delay is outside the scope of this standard. If a timeslot is not available, the next higher layer may issue the MLME-TRLE-MANAGEMENT.response primitive with ManagementType parameter set to JOIN and a status of SLOT_FULL. If it fails to determine the relaying delay, the next higher layer may issue the MLME-TRLE-MANAGEMENT.response primitive with ManagementType parameter set to JOIN and a status of RELAY_FULL. Otherwise, the next higher layer of the TRLE-enabled PAN coordinator may initiate a response using an MLME-TRLE-MANAGEMENT.response primitive with the ManagementType parameter set to JOIN and a status of SUCCESS, as described in 10.37.5.3.3.

When the MLME of the TRLE PAN coordinator receives the MLME-TRLE-MANAGEMENT.response primitive, it generates a TRLE Management Response command with the Management Type field set to Join, as described in 10.37.5.2.2, and attempts to send a command to the device requesting TRLE path formation. The timeslot in which the TRLE Management Response command will be transmitted shall be selected according the TxGrade parameter of the response primitive, as described in 10.37.4.6. The identifier of the timeslot is set to the Slot ID field and the Superframe ID field of the TRLE Descriptor IE. The TxGrade parameter of the response primitive is set to the Grade of Link Access field of the TRLE Descriptor IE. The Timestamp field of the TRLE Management Response command is set to the time of the timeslot specified by the Slot ID field and the Superframe ID field of the TRLE Descriptor IE. The TRLE Descriptor IE shall be included in the Header IE field of the TRLE Management Response command.

On reception of the TRLE Management Response command, the TRLE PAN relay or TRLE-enabled device informs the next higher layer of the association response by using an MLME-TRLE-MANAGEMENT.confirm primitive with the ManagementType parameter set to JOIN, as described in 10.37.5.3.4.

After joining a TRLE path, the next higher layer of the TRLE PAN relay may instruct through the MLME-TRLE-MANAGEMENT.request primitive with the ManagementType parameter set to RELAY_ON, as described in 10.37.5.3.1, that the MLME configures the following MAC PIB attributes:

- *macNumPrioritizedDevice* shall be set equal to the NumPrioritizedDevice parameter of the MLME-TRLE-MANAGEMENT.request primitive.
- *macNumCoordSlot* shall be set equal to the NumCoordSlot parameter of the MLME-TRLE-MANAGEMENT.request primitive.
- *macSyncRelayingOffset* shall be set equal to the SyncRelayingOffset parameter of the MLME-TRLE-MANAGEMENT.request primitive.

The MAC sublayer of the TRLE PAN relay shall begin relaying frames, as described in 10.37.4.4. The next higher layer shall be notified of the result of initiating the PAN relay through the MLME-TRLE-MANAGEMENT.confirm primitive with the ManagementType parameter set to RELAY_ON, as described in 10.37.5.3.4.

In order for the TRLE PAN relay or TRLE-enabled device to leave the TRLE-enabled PAN, the next higher layer should halt the relaying by issuing the MLME-TRLE-MANAGEMENT.request primitive with the ManagementType parameter set to RELAY_OFF. The next higher layer shall be notified of the result of halting the relaying through the MLME-TRLE-MANAGEMENT.confirm primitive with the ManagementType parameter set to RELAY_OFF, as described in 10.37.5.3.4.

After halting the relaying, the next higher layer may request through the MLME-TRLE-MANAGEMENT.request primitive with the ManagementType parameter set to LEAVE and TxGrade

parameter set to GRADE_0 for the TRLE PAN relay or set to GRADE_2 for the TRLE-enabled device, as described in 10.37.5.3.1.

The MAC sublayer of the TRLE PAN relay shall initiate the leaving procedure by sending a TRLE Management Request command with the Management Type field set to Leave, as described in 10.37.5.2.1, through the inner coordinator to the TRLE-enabled PAN coordinator.

The TRLE-enabled PAN coordinator indicates the reception of a TRLE Management Request command through the MLME-TRLE-MANAGEMENT.indication primitive with the ManagementType parameter set to LEAVE, as described in 10.37.5.3.2. The next higher layer of the TRLE PAN coordinator may confirm that the device requesting disassociation is on a relaying path and determine whether it is possible to leave the relaying path.

If it is admitted, the next higher layer of the TRLE-enabled PAN coordinator may initiate a response using an MLME-TRLE-MANAGEMENT.response primitive with the ManagementType parameter set to LEAVE and a status of SUCCESS, as described in 10.37.5.3.3. Otherwise, the status parameter of the response primitive is set to NOT_FOUND or NOT_CONFIRMED.

When the MLME of the TRLE PAN coordinator receives the MLME-TRLE-MANAGEMENT.response primitive, it generates a TRLE Management Response command with the Management Type field set to Leave, as described in 10.37.5.2.2, and attempts to send the command to the requesting device.

On the reception of the TRLE Management Response command, the TRLE PAN relay or TRLE-enabled device informs the next higher layer using an MLME-TRLE-MANAGEMENT.confirm primitive with ManagementType parameter set to LEAVE, as described in 10.37.5.3.4. The status parameter in the MLME-TRLE-MANAGEMENT.confirm primitive is set to the Management Status field of the Management Response command.

After leaving a TRLE path, the next higher layer may disassociate from the DSME-enabled PAN, as described in 10.21.3.

10.37.4.4 Multihop relaying

The TRLE-enabled PAN coordinator and TRLE PAN relays may provide multihop relaying to extend the range of the link.

On receipt of a frame, the MAC sublayer of a TRLE PAN relay shall perform frame filtering, as described in 10.37.3.2.

If a short destination address included in the filtered frame matches *macShortAddress*, or if an extended destination address included in the filtered frame matches *macExtendedAddress*, the frame shall be handled as described in 6.6.2.

A frame having a destination address as the broadcast address shall be handled as described in 6.6.2 and shall also be relayed by the MAC sublayer.

If a short destination address included in the filtered frame does not match *macShortAddress*, or if an extended destination address included in the filtered frame does not match *macExtendedAddress*, the frame shall be relayed at the MAC sublayer.

If the Relaying Direction field of the TRLE Descriptor IE is set to one and the Relaying Tier Identifier field is equal to *macRelayingTier* – 1, the frame shall be relayed outward. If the Relaying Direction field of the TRLE Descriptor IE is set to zero and the Relaying Tier Identifier field is equal to *macRelayingTier* + 1, the frame shall be relayed inward. Otherwise, the TRLE PAN relay shall discard the frame.

If the PAN Relay Address field of the TRLE Descriptor IE included in the relayed outward frame, with the exception of a beacon frame, does not match *macShortAddress*, the TRLE PAN relay shall discard the frame. If the PAN Relay Address field of the TRLE Descriptor IE included in the relayed inward frame, with the exception of a TRLE Management Request command with the Management Type field set to Join, does not match one of the outer adjacent PAN relays in the *macPanRelayList*, the TRLE PAN relay shall discard the frame.

If the frame is the TRLE Management Request command with the Management Type field set to Join or the TRLE Management Response command with the Management Type field set to Path, the PAN relay List Count field of the Relaying Path List field is increased by one and the TRLE Descriptor IE is copied to the end of the PAN relay List field of the Relaying Path List field of the command.

Before relaying the frame, the TRLE Descriptor IE shall be updated. The Relaying Tier Identifier field is changed to the PIB attribute *macRelayingTier*. The TRLE PAN Relay Address field of a beacon frame or the frame relayed inward is changed to the PIB attribute *macShortAddress*. The TRLE PAN Relay Address field of the relayed outward frame, with the exception of a beacon, is changed to one of the outer adjacent PAN relays in the *macPanRelayList*, indexed by the destination address of the MHR field. The Slot ID field and Superframe ID field are set to the timeslot assigned for relaying the frame, as described in 10.37.4.6.

If the Grade of Link Access field of the TRLE Descriptor IE is set to 0b00 or 0b01, the Frame Type field indicates a Data frame or MAC command relayed inward, and the AR field is set to request an acknowledgment, the MAC sublayer shall send an Enh-Ack frame having a destination address set to the TRLE PAN Relay Address field of the TRLE Descriptor IE. Prior to the transmission of the Enh-Ack frame, the sequence number included in the received Data frame or MAC command shall be copied into the Sequence Number field of the Enh-Ack frame, and the TRLE Descriptor IE shall be included in the Header IE of the Enh-Ack frame.

The frame is relayed either outward or inward, as shown in Figure 10-279. The beacon generated by the TRLE PAN coordinator shall be relayed outward after delaying *superframe duration* × *RelayingDelay*. The *RelayingDelay* is calculated as *macSyncRelayingOffset* – *macInnerRelayingOffset*, if *macSyncRelayingOffset* is larger than *macInnerRelayingOffset*. Otherwise, the *RelayingDelay* is calculated as $2^{(BO-SO)} - (macInnerRelayingOffset - macSyncRelayingOffset)$.

A frame received in a prioritized device timeslot shall be relayed inward within the prioritized device timeslot. If transmission cannot be completed by the end of the prioritized device timeslot, the frame shall be relayed in the prioritized device timeslot of the next superframe.

A frame received in a coordinator timeslot shall be relayed outward within the coordinator timeslot. If transmission cannot be completed by the end of the coordinator timeslot, the frame shall be relayed in the coordinator timeslot of the next superframe.

A frame received in a bidirectional device timeslot from the inner PAN relay shall be relayed outward after delaying *superframe duration* × *RelayingDelay*. A frame received from the outer PAN relay shall be relayed after delaying *superframe duration* × [$2^{(BO-SO)} - RelayingDelay$].

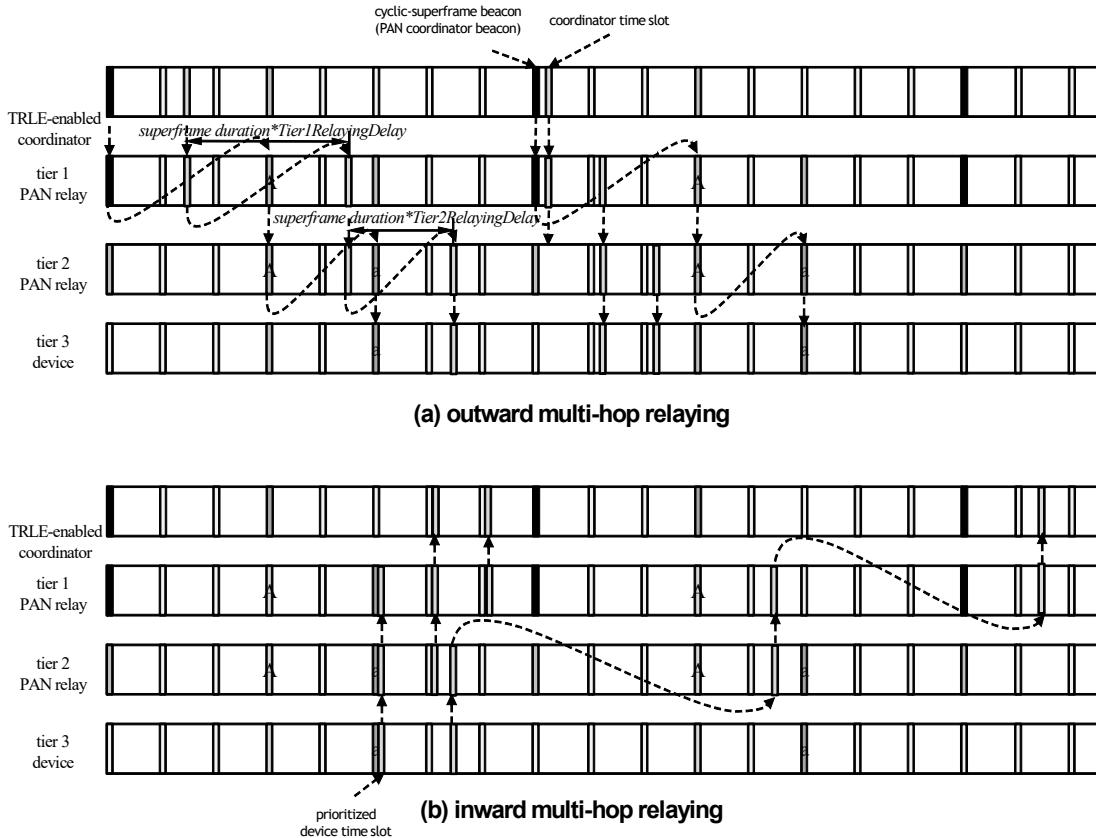


Figure 10-279—Synchronous multihop frame relaying

10.37.4.5 TRLE path maintenance

After starting a TRLE-enabled PAN, the PAN coordinator may need to check the status of a device, collect information on the configuration of PAN relays on the TRLE relaying paths, and maintain time-synchronization.

To search for activated devices in a TRLE-enabled PAN, the next higher layer may issue the MLME-TRLE-MANAGEMENT.request primitive with the ManagementType parameter set to HELLO and the DstAddr parameter, as described in 10.37.5.3.1. The TRLE-enabled PAN coordinator only shall be allowed to set the DstAddr parameter of the request primitive to the broadcast address.

The MAC sublayer shall send the TRLE Management Request command with the Management Type field set to HELLO.

The MLME shall notify the reception of a TRLE Management Request command through the MLME-TRLE-MANAGEMENT.indication primitive with the ManagementType parameter set to HELLO. If the destination address of the TRLE Management Request command is set to the broadcast address, the MAC sublayer shall relay the TRLE Management Request command to the outer PAN relays in the *macPanRelayList*.

The next higher layer may set the device configuration, as defined in 10.37.5.2.2, through the MLME-TRLE-MANAGEMENT.response primitive, defined in 10.37.5.3.3, with the ManagementType parameter set to HELLO.

When the MLME receives the MLME-TRLE-MANAGEMENT.response primitive with the ManagementType parameter set to HELLO, it generates a TRLE Management Response command with the Management Type field set to HELLO, as described in 10.37.5.2.2, and attempts to send the response command to the requesting device.

The next higher layer shall be notified of a reception of a TRLE Management Response command with the Management Type field set to HELLO, through the MLME-TRLE-MANAGEMENT.confirm primitive with ManagementType parameter set to HELLO.

To get information on the relaying path configuration to a device, the next higher layer may issue the MLME-TRLE-MANAGEMENT.request primitive with the ManagementType parameter set to PATH.

The MAC sublayer shall send the TRLE Management Request command with the Management Type field set to Path, as described in 10.37.5.2.1. The request command shall be relayed to the destination device.

The MLME shall notify the next higher layer of the reception of a TRLE Management Request command with the Management Type field set to Path by issuing the MLME-TRLE-MANAGEMENT.indication primitive with the ManagementType parameter set to PATH.

The next higher layer may report the device configuration, as defined in 10.37.5.2.2, through the MLME-TRLE-MANAGEMENT.response primitive with the ManagementType parameter set to PATH.

When the MLME receives the MLME-TRLE-MANAGEMENT.response primitive with the ManagementType parameter set to PATH, it generates a TRLE Management Response command with the Management Type field set to Path, as described in 10.37.5.2.2, and attempts to send the command to the device requesting the path configuration. The relaying path configuration is added to the Relay Path List field of the TRLE Management Response command at the MAC sublayer of the PAN relays on the relaying path to the requesting device, as described in 10.37.4.4.

The next higher layer shall be notified of the reception of a TRLE Management Response command with the Management Type field set to Path, through the MLME-TRLE-MANAGEMENT.confirm primitive with the ManagementType parameter set to PATH, as described in 10.37.5.3.4.

The PAN relays and end devices in a TRLE-enabled PAN shall be synchronized with the time of the TRLE-enabled PAN coordinator after joining the TRLE-enabled PAN.

The TRLE-enabled PAN coordinator shall advertise the time, obtained from the local clock of the TRLE-enabled PAN, outward to the PAN relays and end devices via the Beacon Timestamp field of the DSME PAN Descriptor IE in a beacon frame. The time, obtained from the local clock of a TRLE PAN relay, may be distributed via the Timestamp field in the TRLE Management Request command and the TRLE Management Response command. The Timestamp field shall specify the start time of a timeslot where the frame is to be transmitted.

The PAN relays and end devices compensate for the clock drift based on the statistical variance of the difference in the real start time of a given slot and the expected start time.

The PAN relay maintains the status of the neighbored PAN relays by watching the beacon frame of the inner PAN relay and of the outer PAN relay.

If the PAN relay misses the beacon frame of the inner PAN relay for $macBeaconMissingLimit \times BI$, the PAN relay selects one of the adjacent inner PAN relays in the $macPanRelayList$, starts to join to the TRLE-enabled PAN coordinator, and replicates the beacon frame of the TRLE-enabled PAN coordinator until finishing the joining process. If the PAN relay fails to find the adjacent inner PAN relay, the PAN relay starts to search any neighbored inner PAN relay, as described in 10.37.4.3.

If the PAN relay misses the beacon frame of the adjacent outer PAN relay for $macBeaconMissingLimit \times BI$, the PAN relay checks the status of the adjacent outer PAN relay by sending the TRLE Management Request command with the Management Type field set to HELLO. If there is no response, the PAN relay makes the adjacent outer PAN relay leave the TRLE-enabled PAN by sending the TRLE Management Request command with the Management Type field set to Leave and the source address set to the address of the adjacent outer PAN relay.

10.37.4.6 Multiple grades of link access

In a TRLE-enabled PAN, in order to accommodate various qualities of service requirements for relaying frames between the TRLE-enabled PAN coordinator and a TRLE PAN relay, three grades of link access are provided: grade 0 for delay sensitive data transmission, grade 1 for reliable data transmission, and grade 2 for best effort data transmission.

For grade 0 link access, to send a frame inward, a device shall wait until the earliest prioritized device timeslot. If the device fails to transmit the data in the prioritized device timeslot, the device will continue trying to transmit the data in the next prioritized device timeslot. To send a frame outward, a device shall use the earliest coordinator timeslot.

For grade 1 link access, a device shall wait until the earliest bidirectional timeslot assigned to the device and transmit the data. If the device fails to transmit the data, the device will keep searching for the next available bidirectional timeslot for the duration of the cyclic-superframe or will search the next cyclic-superframe for an opportunity to transmit the data.

For grade 2 link access, a device shall wait until the earliest bidirectional timeslot assigned to the device and transmit the data without requiring an acknowledgment.

A frame with grade 0 or grade 1 link access shall be acknowledged hop-by-hop and end-to-end. At a TRLE PAN relay, if the Grade of Link Access field of the TRLE Descriptor IE is set to 0b00 or 0b01, the Frame Type field indicates a Data frame or MAC command relayed inward, and the AR field is set to request an acknowledgment, the MAC sublayer shall send an Enh-Ack frame within the same timeslot in which the frame is received. If it fails to complete transmission of the Enh-Ack frame before the end of the timeslot, the Enh-Ack frame shall be sent in the coordinator timeslot of the following superframe.

10.37.5 MAC services for the TRLE-enabled PAN

10.37.5.1 TRLE IEs

10.37.5.1.1 TRLE Descriptor IE

The TRLE Descriptor IE shall be included in Enhanced Beacon frame, Data frame, Enh-Ack frame, and MAC commands that are sent in a TRLE-enabled PAN.

The TRLE Descriptor IE Content field shall be formatted as illustrated in Figure 10-280.

Bits: 3	1	2	4	14	16
Relaying Tier Identifier	Relaying Direction	Grade of Link Access	Slot ID	Superframe ID	PAN Relay Address

Figure 10-280—TRLE Descriptor IE Content field format

The Relaying Tier Identifier field shall be set to the identifier of the relaying tier of the TRLE PAN relay by which this frame will be transmitted. A value of zero shall indicate tier 0 where the TRLE-enabled PAN coordinator is located.

The Relaying Direction field shall be set to one if the frame is relayed outward. Otherwise, it is set to zero.

The Grade of Link access field shall be set to the TxGrade parameter stated in the primitive, as defined in 10.37.5.3.

The Slot ID field contains the ID of the timeslot in which this frame will be transmitted.

The Superframe ID field contains the ID of the superframe in which this frame will be transmitted.

The PAN Relay Address field of an inward frame or a beacon frame shall be set to the PIB attribute *macShortAddress* of the TRLE PAN relay by which this frame will be transmitted. The PAN Relay Address field of an outward frame, with the exception of a beacon frame, shall be set to one of the neighboring PAN relays in the *macPanRelayList*, indexed by the destination address of the MHR field.

10.37.5.2 TRLE commands

10.37.5.2.1 TRLE Management Request command

The TRLE Management Request command allows a device with its PIB attribute *macTrleEnabled* set to TRUE to request to join a TRLE relaying path, leave the TRLE relaying path, report relaying path information, or assign a device slot.

Only devices that have been assigned a short address shall send this command.

The Destination Addressing Mode and the Source Addressing Mode fields of the Frame Control field shall both be set to two (i.e., 16-bit short addressing).

The Frame Pending field of the Frame Control field shall be set to zero and ignored upon reception.

The Source PAN ID field shall contain the value of *macPanId*, and the Source Address field shall contain the value of *macShortAddress*.

The Destination PAN ID field shall contain the value of *macPanId*, and the Destination Address field shall be set to the short address of the destination device.

The TRLE Management Request command Content field shall be formatted as illustrated in Figure 10-281.

Octets: 1	0/6	0/variable	0/1	0/variable
Management Type	Timestamp	Beacon Bitmap	Number of Slots	Relaying Path List

Figure 10-281—TRLE Management Request command Content field format

The Management Type field shall be set as one of the non-reserved values listed in Table 10-186.

The Timestamp field shall contain the time, in microseconds, of the timeslot in which the TRLE Management Request command will be transmitted. This field is valid only if the value of the Management Type field is 0x02 or 0x03.

Table 10-186—Values of the Management Type field

Management Type value	Description
0x00	Join
0x01	Leave
0x02	HELLO
0x03	Path
0x04–0xff	Reserved

The Beacon Bitmap field is described in 10.4.11.1. The Beacon Bitmap field shall be set to the BeaconBitmap parameter of the MLME-TRLE-MANAGEMENT.request primitive. This field is valid only if the value of the Management Type field is 0x00.

The Number of Slots field shall contain the number of bidirectional device timeslots that this command is requesting. The Number of Slots field shall be set to the NumBidirectionalDeviceSlot parameter of the MLME-TRLE-MANAGEMENT.request primitive. This field is valid only if the value of the Management Type field is set to 0x00.

The Relaying Path List field shall be formatted as illustrated in Figure 10-282.

Octets: 1	variable
PAN Relay List Count	PAN Relay List

Figure 10-282—TRLE Relaying Path Descriptor field format

The PAN Relay List Count field shall contain the number of PAN relays in the PAN Relay List field.

The PAN Relay List field shall contain the TRLE descriptors on a TRLE path, as defined in 10.37.5.1.1.

10.37.5.2.2 TRLE Management Response command

The TRLE Management Response command allows the TRLE-enabled PAN coordinator or the TRLE PAN relay to communicate the results of a request to join a TRLE relaying path, leave the TRLE relaying path, report relaying path information, or assign a device slot.

Only devices that have been assigned a short address shall send this command.

The Destination Addressing Mode and the Source Addressing Mode fields of the Frame Control field shall both be set to two (i.e., 16-bit short addressing).

The Frame Pending field of the Frame Control field shall be set to zero and ignored upon reception.

The Source PAN ID field shall contain the value of *macPanId*, and the Source Address field shall contain the value of *macShortAddress*.

The Destination PAN ID field shall contain the value of *macPanId*, and the Destination Address field shall be set to the short address of the destination device.

The TRLE Management Response command Content field shall be formatted as illustrated in Figure 10-283.

Octets: 1	1	0/variable
Management Type	Management Status	TRLE Management Information

Figure 10-283—TRLE Management Response command Content field format

The Management Type field is described in 10.37.5.2.1.

The Management Status field shall be set to the status parameter of the MLME-TRLE-MANAGEMENT.response primitive. This field is valid only if the Management Type field is set to 0x00.

The TRLE Management Information field shall be formatted as illustrated in Figure 10-284.

0/6	0/2	0/variable	0/variable	0/variable
Timestamp	Sync Relaying Offset	Bidirectional Device Slot List	Relay Descriptor	Relaying Path List

Figure 10-284—TRLE Management Information field format

The Timestamp field shall contain the time, in microseconds, of the timeslot in which the TRLE Management Response command will be transmitted. This field is valid only if the Management Type field is set to 0x00.

The Sync Relaying Offset field shall contain the relaying delay of the cyclic-superframe of a PAN relay compared to the cyclic-superframe of the TRLE-enabled PAN coordinator, which is specified in the number of superframe duration. The Sync Relaying Offset field shall be set to the SyncRelayingOffset parameter of the MLME-TRLE-MANAGEMENT.response primitive. This field is valid only if the ManagementType field is set to 0x00.

The Bidirectional Device Slot List field shall be set to the BidirectionalDeviceSlotList parameter of the MLME-TRLE-MANAGEMENT.response primitive, as defined in 10.37.5.3.3.

The Bidirectional Device Slot List field shall be formatted as illustrated in Figure 10-285.

Octets: 1	variable
Bidirectional Device Slot List Count	Bidirectional Device Slot Descriptor

Figure 10-285—Bidirectional Device Slot List field format

The Bidirectional Device Slot List Count field shall contain the number of the Bidirectional Device Slot Descriptor in the Bidirectional Device Slot List field.

The Bidirectional Device Slot Descriptor field shall be formatted as illustrated in Figure 10-286.

Octets: 1	2
Slot ID	Superframe ID

Figure 10-286—Bidirectional Device Slot Descriptor format

The Slot ID field contains the ID of the timeslot of the superframe in which a bidirectional device timeslot is assigned. The slot ID is the sequence number of the timeslot in a superframe beginning from zero.

The Superframe ID field contains the ID of the superframe in which a bidirectional device timeslot is assigned. The superframe ID is the sequence number of the superframe in a cyclic-superframe beginning from zero. This field is valid only if the Management Type field is set to 0x02 or 0x03.

The Relay Descriptor field shall be set to the RelayDescriptor parameter of the MLME-TRLE-MANAGEMENT.response primitive, as described in 10.37.5.3.3.

The Relay Descriptor field shall be formatted as illustrated in Figure 10-287.

Octets: 2	1	2	2	2	3	variable
Device Address	Relaying Tier Identifier	Sync Relaying Offset	Inner PAN Relay Address	Inner Relaying Offset	Primary Device Slot Descriptor	Beacon Bitmap

Figure 10-287—TRLE Relay Descriptor format

The Device Address field shall be set to the short address of the TRLE device that this command is requesting.

The Relaying Tier Identifier field shall contain the identifier of the relaying tier of the TRLE device that this command is requesting.

The Sync Relaying Offset field shall contain the relaying delay of the TRLE device that this command is requesting.

The Inner PAN Relay Address field shall be set to the short address of the inner PAN relay of the TRLE device that this command is requesting.

The Inner Relaying Offset field shall contain the relaying delay of the inner PAN relay of the TRLE device that this command is requesting.

The Primary Device Slot Descriptor field shall contain the primary bidirectional device slot of the TRLE device that this command is requesting and shall be formatted as illustrated in Figure 10-285.

The Beacon Bitmap field is described in 10.4.11.1.

The Relaying Path List field is described in 10.37.5.2.1. This field is valid only if the Management Type field is set to 0x03.

10.37.5.3 Primitives for managing the TRLE-enabled PAN

10.37.5.3.1 MLME-TRLE-MANAGEMENT.request

The MLME-TRLE-MANAGEMENT.request primitive requests to either start a TRLE-enabled PAN, join a TRLE relaying path, leave the TRLE relaying path, or report relaying path information.

The semantics of this primitive are as follows:

```
MLME-TRLE-MANAGEMENT.request (
    ManagementType,
    DstAddrMode,
    DstAddr,
    TxGrade,
    NumPrioritizedDeviceSlot,
    NumCoordSlot,
    NumBidirectionalDeviceSlot,
    SrcRelayingTier,
    BeaconBitmap,
    InnerRelayingOffset,
    SyncRelayingOffset,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-187.

Table 10-187—MLME-TRLE-MANAGEMENT.request parameters

Name	Type	Valid range	Description
ManagementType	Enumeration	START, JOIN, LEAVE, RELAY_ON, RELAY_OFF, HELLO, PATH	The type of TRLE-enabled PAN management to be performed: START = 0, JOIN = 1, LEAVE = 2, RELAY_ON = 3, RELAY_OFF = 4, HELLO = 5, PATH = 6.
DstAddrMode	Enumeration	NONE, SHORT, EXTENDED	The destination addressing mode for this primitive.
DstAddr	—	As specified by DstAddrMode parameter	The address of the device for which the frame was intended.
TxGrade	Enumeration	GRADE_0, GRADE_1, GRADE_2	The grade of link access to be used: GRADE_0 = 0, GRADE_1 = 1, GRADE_2 = 2.
NumPrioritizedDevice	Integer	1–6	The number of timeslots in a superframe assigned as the prioritized device slots.
NumCoordSlot	Integer	1–6	The number of timeslots in a superframe assigned as the coordinator slots.
NumBidirectionalDeviceSlot	Integer	0–5	The number of timeslots in a cyclic-superframe assigned as the bidirectional device slot.
SrcRelayingTier	Integer	0–7	The identifier of the relaying tier in which a device is placed. The relaying tier of the PAN coordinator is zero.

Table 10-187—MLME-TRLE-MANAGEMENT.request parameters (continued)

Name	Type	Valid range	Description
BeaconBitmap	Bitmap	As defined in 10.4.11.1	The beacon bitmap as specified in the received Enhanced Beacon frame.
InnerRelayingOffset	Integer	0x0000–0x7fff	The index of the superframe at which the inner PAN relay starts a cyclic-superframe. If the inner PAN relay of a device is the TRLE-enabled PAN coordinator, the InnerRelayingOffset of the device is zero.
SyncRelayingOffset	Integer	0x0000–0x7fff	The index of the superframe at which a device starts a cyclic-superframe. The SyncRelayingOffset of the PAN coordinator is zero.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

The MLME-TRLE-MANAGEMENT.request primitive may be used by the TRLE-enabled PAN management layer to establish, operate, or maintain a TRLE relaying path.

When the ManagementType parameter is set to START, all parameters except NumPrioritizedDevice and NumCoordSlot shall be ignored, and the MAC sublayer shall attempt to update the cyclic-superframe specification and begin the transmission of the TRLE Relaying IE in an enhanced beacon.

When the ManagementType parameter is set to JOIN, all parameters except DstAddrMode, DstAddr, TxGrade, SrcRelayingTier, InnerRelayingOffset, BeaconBitmap, and NumBidirectionalDeviceSlot shall be ignored. The MAC sublayer shall attempt to update the appropriate MAC PIB attributes, as described in 10.37.4.3, and generate a TRLE Management Request command with the Management Type field set to Join, as defined in 10.37.5.2.1.

When the ManagementType parameter is set to LEAVE, all parameters except DstAddrMode, DstAddr, and TxGrade shall be ignored, and the MAC sublayer shall attempt to generate a TRLE Management Request command with the Management Type field set to Leave.

When the ManagementType parameter is set to RELAYING_ON, all parameters except NumPrioritizedDevice, NumCoordSlot, and SyncRelayingOffset shall be ignored, and the MAC sublayer shall begin relaying frames, as described in 10.37.4.4.

When the ManagementType parameter is set to RELAYING_OFF, all parameters shall be ignored, and the MAC sublayer shall stop relaying frames.

When the ManagementType parameter is set to HELLO, all parameters except DstAddrMode and DstAddr shall be ignored, and the MAC sublayer shall attempt to generate a TRLE Management Request command with the Management Type field set to HELLO.

When the ManagementType parameter is set to PATH, all parameters except DstAddrMode and DstAddr shall be ignored, and the MAC sublayer shall attempt to generate a TRLE Management Request command with the Management Type field set to Path.

The TRLE Management Request command is relayed to the DstAddr with the grade of link access specified in TxGrade.

Typically, the TRLE Management Request command should not be implemented using security. However, if the device shares a key with the coordinator, then security may be specified.

10.37.5.3.2 MLME-TRLE-MANAGEMENT.indication

The MLME-TRLE-MANAGEMENT.indication is used to indicate the reception of a TRLE-Management Request command.

The semantics of this primitive are as follows:

```
MLME-TRLE-MANAGEMENT.indication (
    ManagementType,
    SrcAddrMode,
    SrcAddr,
    TxGrade,
    Timestamp,
    BeaconBitmap,
    NumBidirectionalDeviceSlot,
    RelayingPathList,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-188.

Table 10-188—MLME-TRLE-MANAGEMENT.indication parameters

Name	Type	Valid range	Description
ManagementType	Enumeration	START, JOIN, LEAVE, RELAY_ON, RELAY_OFF, HELLO, PATH	The type of TRLE-enabled PAN management to be performed: START = 0, JOIN = 1, LEAVE = 2, RELAY_ON = 3, RELAY_OFF = 4, HELLO = 5, PATH = 6.
SrcAddrMode	Enumeration	NONE, SHORT, EXTENDED	The source addressing mode for this primitive.
SrcAddr	—	As specified by SrcAddrMode parameter	The address of the device for which the frame was generated.
TxGrade	Enumeration	GRADE_0, GRADE_1, GRADE_2	The grade of link access to be used: GRADE_0 = 0, GRADE_1 = 1, GRADE_2 = 2.
Timestamp	Integer	0x000000–0xffffffff	The time at which the TRLE Management Request command was transmitted. The format of timestamp is specified in 6.5.3.
BeaconBitmap	Bitmap	As defined in 10.4.11.1	The beacon bitmap as specified in the received Enhanced Beacon frame.
NumBidirectionalDeviceSlot	Integer	0–5	The number of timeslots in a cyclic-superframe assigned as the bidirectional device slot.
RelayingPathList	List of octets	As defined in 10.37.5.2.1	The relaying information on a TRLE relaying path.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

This primitive is generated by the MLME of a device and issued to its next higher layer upon the reception of a TRLE Management Request command.

When the ManagementType parameter is set to JOIN, all parameters except SrcAddrMode, SrcAddr, TxGrade, BeaconBitmap, NumBidirectionalDeviceSlot, and RelayingPathList shall be ignored.

When the ManagementType parameter is set to LEAVE, all parameters except SrcAddrMode, SrcAddr, and TxGrade shall be ignored.

When the ManagementType parameter is set to HELLO, all parameters except SrcAddrMode, SrcAddr, TxGrade, and Timestamp shall be ignored.

When the ManagementType parameter is set to PATH, all parameters except SrcAddrMode, SrcAddr, TxGrade, and Timestamp shall be ignored.

10.37.5.3.3 MLME-TRLE-MANAGEMENT.response

This primitive allows the next higher layer of a device to respond to the MLME-TRLE-MANAGEMENT.indication primitive.

The semantics of this primitive are as follows:

```
MLME-TRLE-MANAGEMENT.response (
    ManagementType,
    DstAddrMode,
    DstAddr,
    TxGrade,
    Status,
    NumPrioritizedDeviceSlot,
    NumCoordSlot,
    NumBidirectionalDeviceSlot,
    SyncRelayingOffset,
    BidirectionalDeviceSlotList,
    RelayDescriptor,
    RelayingPathList,
    SecurityParams
)
```

The primitive parameters are defined in Table 10-189.

Table 10-189—MLME-TRLE-MANAGEMENT.response parameters

Name	Type	Valid range	Description
ManagementType	Enumeration	START, JOIN, LEAVE, RELAY_ON, RELAY_OFF, HELLO, PATH	The type of TRLE-enabled PAN management to be performed: START = 0, JOIN = 1, LEAVE = 2, RELAY_ON = 3, RELAY_OFF = 4, HELLO = 5, PATH = 6.
DstAddrMode	Enumeration	NONE, SHORT EXTENDED	The destination addressing mode for this primitive.
DstAddr	—	As specified by DstAddrMode parameter	The address of the device for which the frame was intended.

Table 10-189—MLME-TRLE-MANAGEMENT.response parameters (continued)

Name	Type	Valid range	Description
TxGrade	Enumeration	GRADE_0, GRADE_1, GRADE_2	The grade of link access to be used: GRADE_0 = 0, GRADE_1 = 1, GRADE_2 = 2.
Status	Enumeration	As defined in 10.37.5.3.4	The status of the management attempt.
NumPrioritizedDevice	Integer	1–6	The number of timeslots in a superframe assigned as the prioritized device slots.
NumCoordSlot	Integer	1–6	The number of timeslots in a superframe assigned as the coordinator slots.
NumBidirectionalDeviceSlot	Integer	0–5	The number of timeslots in a cyclic-superframe assigned as the bidirectional device slot.
SyncRelayingOffset	Integer	0x0000–0x7fff	The index of the superframe at which a device starts a cyclic-superframe. The SyncRelayingOffset of the PAN coordinator is zero.
BidirectionalDeviceSlotList	Set of octets	As described in 10.37.5.2.2	The set of bidirectional device timeslots to be allocated for the device.
RelayDescriptor	Set of octets	As defined in 10.37.5.2.2	The relaying specification of a device.
RelayingPathList	Set of octets	As defined in 10.37.5.2.1	The relaying information on a TRLE relaying path.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.

On receipt of the MLME-TRLE-MANAGEMENT.response primitive, the MLME of the device shall generate a TRLE Management Response command.

When the ManagementType parameter is set to JOIN, all parameters except DstAddrMode, DstAddr, TxGrade, Status, NumPrioritizedDeviceSlot, NumCoordSlot, SyncRelayingOffset, NumBidirectionalDeviceSlot, and BidirectionalDeviceSlotList shall be ignored. The MAC sublayer shall generate a TRLE Management Response command with the Management Type field set to Join, as defined in 10.37.5.2.2.

When the ManagementType parameter is set to LEAVE, all parameters except DstAddrMode, DstAddr, TxGrade, and Status shall be ignored, and the MAC sublayer shall generate a TRLE Management Response command with the Management Type field set to Leave.

When the ManagementType parameter is set to HELLO, all parameters except DstAddrMode, DstAddr, TxGrade, Status, and RelayDescriptor shall be ignored. The MAC sublayer shall generate a TRLE Management Response command with Management Type field set to HELLO.

When the ManagementType parameter is set to PATH, all parameters except DstAddrMode, DstAddr, TxGrade, Status, and RelayDescriptor shall be ignored. The MAC sublayer shall generate a TRLE Management Response command with the Management Type field set to Path.

10.37.5.3.4 MLME-TRLE-MANAGEMENT.confirm

The MLME-TRLE-MANAGEMENT.confirm primitive reports the result of the TRLE management request.

The semantics of this primitive are as follows:

```
MLME-TRLE-MANAGEMENT.confirm(
    ManagementType,
    SrcAddrMode,
    SrcAddr,
    Timestamp,
    NumPrioritizedDeviceSlot,
    NumCoordSlot,
    SyncRelayingOffset,
    NumBidirectionalDeviceSlot,
    BidirectionalDeviceSlotList,
    RelayDescriptor,
    RelayingPathList,
    SecurityParams,
    Status
)
```

The primitive parameters are defined in Table 10-190.

Table 10-190—MLME-TRLE-MANAGEMENT.confirm parameters

Name	Type	Valid range	Description
ManagementType	Enumeration	START, JOIN, LEAVE, RELAY_ON, RELAY_OFF, HELLO, PATH	The type of TRLE-enabled PAN management to be performed: START = 0, JOIN = 1, LEAVE = 2, RELAY_ON = 3, RELAY_OFF = 4, HELLO = 5, PATH = 6.
SrcAddrMode	Enumeration	NONE, SHORT, EXTENDED	The source addressing mode for this primitive.
SrcAddr	—	As specified by SrcAddrMode parameter	The address of the device for which the frame was generated.
Timestamp	Integer	0x000000–0xffffffff	The time at which the TRLE Management Request command was transmitted. The format of timestamp is specified in 6.5.3.
NumPrioritizedDevice	Integer	1–6	The number of timeslots in a superframe assigned as the prioritized device slots.
NumCoordSlot	Integer	1–6	The number of timeslots in a superframe assigned as the coordinator slots.
NumBidirectionalDeviceSlot	Integer	0–5	The number of timeslots in a cyclic-superframe assigned as the bidirectional device slot.

Table 10-190—MLME-TRLE-MANAGEMENT.confirm parameters (continued)

Name	Type	Valid range	Description
SyncRelayingOffset	Integer	0x0000–0x7fff	The index of the superframe at which a device starts a cyclic-superframe. The SyncRelayingOffset of the PAN coordinator is zero.
BidirectionalDeviceSlotList	Set of octets	As defined in 10.37.5.2.2	The set of bidirectional device timeslots to be allocated for the device.
RelayDescriptor	Set of octets	As defined in 10.37.5.2.2	The relaying specification of a device.
RelayingPathList	Set of octets	As defined in 10.37.5.2.1	The relaying information on a TRLE relaying path.
SecurityParams	Structure	As defined in Table 8-2	As defined in Table 8-2.
Status	Enumeration	SUCCESS, SLOT_FULL, RELAY_FULL, NOT_FOUND, NOT_CONFIRMED, also see 8.2.2	The result of the management request attempt.

The MLME-TRLE-MANAGEMENT.confirm primitive with the ManagementType parameter set to START, RELAY_ON, or RELAY_OFF is generated by the MAC sublayer entity in response to an MLME-TRLE-MANAGEMENT.request primitive.

When the ManagementType parameter is set to START, RELAY_ON, or RELAY_OFF, all parameters except the Status parameter shall be ignored.

On receipt of the MLME-TRLE-MANAGEMENT.confirm primitive with the ManagementType parameter set to JOIN, LEAVE, HELLO, or PATH, the next higher layer is notified of the reception of a TRLE Management Response command.

When the ManagementType parameter is set to JOIN, all parameters except SrcAddrMode, SrcAddr, Status, NumPrioritizedDeviceSlot, NumCoordSlot, SyncRelayingOffset, NumBidirectionalDeviceSlot, and BidirectionalDeviceSlotList shall be ignored.

When the ManagementType parameter is set to LEAVE, all parameters except SrcAddrMode, SrcAddr, and Status shall be ignored.

When the ManagementType parameter is set to HELLO, all parameters except SrcAddrMode, SrcAddr, Status, and RelayDescriptor shall be ignored.

When the ManagementType parameter is set to PATH, all parameters except SrcAddrMode, SrcAddr, Status, RelayDescriptor, and RelayingPathList shall be ignored.

The MLME-TRLE-MANAGEMENT.confirm primitive returns a status of either SUCCESS or the appropriate error code. TRLE specific error codes are:

- SLOT_FULL indicates that the allocation of the bidirectional device timeslot failed.
- RELAY_FULL indicates that the allocation of the superframe for relaying a beacon failed.
- NOT_FOUND indicates that the requesting device cannot be found.
- NOT_CONFIRMED indicates that the request to leave a relaying path is not permitted.

10.37.5.4 TRLE specific MAC PIB attributes

The attributes contained in the MAC PIB for TRLE are presented in Table 10-191.

Table 10-191—TRLE specific MAC PIB attributes

Attribute	Type	Range	Description	Default
<i>macNumPrioritizedDeviceSlot</i>	Integer	1–6	The number of timeslots in a superframe assigned as the prioritized device slots.	3
<i>macNumCoordSlot</i>	Integer	1–6	The number of timeslots in a superframe assigned as the coordinator slots.	3
<i>macNumBidirectionalDeviceSlot</i>	Integer	0–5	The number of timeslots in a cyclic-superframe assigned as the bidirectional device slots.	1
<i>macRelayingTier</i>	Integer	0–7	The identifier of the relaying tier in which a device is placed. The relaying tier of the PAN coordinator is zero.	Implementation specific
<i>macInnerRelayingOffset</i>	Integer	0x0000–0x7fff	The relaying delay of the cyclic-superframe of an inner PAN relay compared with the cyclic-superframe of a TRLE-enabled PAN coordinator, which is specified in the number of superframe duration. If the inner PAN relay of a device is the TRLE-enabled PAN coordinator, the value of <i>macInnerRelayingOffset</i> of the device is zero.	Implementation specific
<i>macSyncRelayingOffset</i>	Integer	0x0000–0x7fff	The relaying delay of the cyclic-superframe of a PAN relay compared with the cyclic-superframe of the TRLE-enabled PAN coordinator, which is specified in the number of superframe duration. The value of <i>macSyncRelayingOffset</i> of the PAN coordinator is zero.	Implementation specific

Table 10-191—TRLE specific MAC PIB attributes (continued)

Attribute	Type	Range	Description	Default
<i>macPanRelayList</i>	PAN relay list	PAN relay list	The list of the neighboring PAN relays, which inform the end devices reached by the PAN relay.	Implementation specific
<i>macBeaconMissingLimit</i>	Integer	0–7	The number of beacons that are missed before starting link recovery processing.	Implementation specific

11. General PHY requirements

11.1 General

11.1.1 Requirements and definitions

Unless otherwise specified, all PHYs use a 2-octet FCS.

The PHY is responsible for the following tasks:

- Activation and deactivation of the radio transceiver
- ED within the current channel
- LQI for received packets
- CCA for CSMA-CA
- Channel frequency selection
- Data transmission and reception
- Precision ranging for UWB PHYs

The PHYs defined in this standard are as follows:

- O-QPSK PHY: DSSS PHY employing O-QPSK modulation, operating in the 780 MHz band, 868 MHz band, 915 MHz band, 2380 MHz band, and 2450 MHz band, as defined in Clause 13.
- BPSK PHY: DSSS PHY employing BPSK modulation, operating in the 868 MHz band and 915 MHz band, as defined in Clause 14.
- CSS PHY: CSS employing differential quadrature phase-shift keying (DQPSK) modulation, operating in the 2450 MHz band, as defined in Clause 15.
- HRP UWB PHY: combined burst position modulation (BPM) and BPSK modulation, operating in the sub-gigahertz and 3–10 GHz bands, as defined in Clause 16.
- GFSK PHY: GFSK, operating in the 920 MHz band, as defined in Clause 17.
- MSK PHY: MSK PHY as defined in Clause 18.
- LRP UWB PHY: low rate pulse UWB PHY as defined in Clause 19.
- SUN FSK PHY: SUN FSK PHY operating in multiple over-the-air data rates in support of SUN applications, as defined in Clause 20.
- SUN OFDM PHY: SUN OFDM PHY operating in multiple over-the-air data rates in support of SUN applications, as defined in Clause 21.
- SUN O-QPSK PHY: SUN O-QPSK PHY operating in multiple over-the-air data rates in support of SUN applications, as defined in Clause 22.
- LECIM DSSS PHY: DSSS PHY operating with characteristics that enable support of LECIM applications, as defined in Clause 23.
- LECIM FSK PHY: FSK PHY operating with characteristics that enable support of LECIM applications, as defined in Clause 24.
- TVWS-FSK PHY: FSK PHY operating in multiple over-the-air data rates in support of various applications in TVWS, as defined in Clause 25.
- TVWS-OFDM PHY: OFDM PHY operating in multiple over-the-air data rates in support of various applications in TVWS, as defined in Clause 26.
- TVWS-NB-OFDM PHY: narrow band OFDM (NB-OFDM) PHY operating in multiple over-the-air data rates in support of various applications in TVWS, as defined in Clause 27.

- RCC LMR PHY: land mobile radio (LMR) for use in RCC applications using one of Gaussian minimum shift keying (GMSK), 4FSK, quadrature phase-shift keying (QPSK), $\pi/4$ DQPSK, or DSSS employing DPSK, as defined in Clause 28.
- RCC DSSS BPSK PHY: a DSSS BPSK PHY for use in RCC applications, as defined in Clause 29.
- CMB O-QPSK PHY: DSSS PHY employing O-QPSK modulation, operating in the 195 MHz, 416 MHz, and 619 MHz bands as defined in 30.1.
- CMB GFSK PHY: GFSK PHY operating in the 195 MHz, 416 MHz, and 619 MHz bands as defined in 30.2.
- TASK PHY: TASK PHY operating in the 433 MHz, 470 MHz, 780 MHz, 863 MHz, 915 MHz, and 2450 MHz bands as defined in Clause 31.
- RS-GFSK PHY: RS-GFSK PHY operating in 169 MHz, 433 MHz, 450 MHz, 470 MHz, 780 MHz, 863 MHz, 870 MHz, 896 MHz, 901 MHz, 915 MHz, 916 MHz, 917 MHz, 928 MHz, 1427 MHz, and 2450 MHz bands as defined in Clause 32.

11.1.2 Operating frequency range

A compliant device shall operate in one or several frequency bands summarized in this subclause.

For devices other than LECIM, TVWS, and RCC PHYs, the frequency bands are listed in Table 11-1.

Table 11-1—Frequency band designations

Band designation (MHz)	Frequency band (MHz)
169	169.400–169.475
195	174–216
416	407–425
433	433.05–434.79
450	450–470
470	470–510
619	608–630
780	779–787
863	863–870
866	865–868
867	866–869
868	868–868.6
870	870–876
896	896–901
901	901–902
915	902–928
915-a	902–928 (alternate)
915-b	902–907.5 and 915–928
915-c	915–928

Table 11-1—Frequency band designations (*continued*)

Band designation (MHz)	Frequency band (MHz)
915-d	915–921
915-e	915–918
917	917–923.5
919	919–923
920	920–928
920-a	920.5–924.5
920-b	920–925
928	928–960 ^a
1427	1427–1518 ^a
2380	2360–2400
2450	2400–2483.5
HRP UWB sub-gigahertz	250–750
HRP UWB low band	3244–4742
HRP UWB high band	5944–10 234
LRP UWB	5624.32–10 435.2

^a Noncontiguous.

NOTE—The 915 MHz-a, 915 MHz-b, and 915 MHz-c frequency bands provide additional PHY parameter definitions to the 915 MHz band.

The frequency bands for devices supporting the LECIM DSSS PHY are shown in Table 11-2.

Table 11-2—LECIM DSSS PHY operating frequency ranges

Band designation	Bandwidth (kHz)	Modulation	Chip rate (kchips/s)
470 MHz	100	BPSK	100
		O-QPSK	200
780 MHz	1000	BPSK	1000
		O-QPSK	2000
863 MHz	100	BPSK	100
		O-QPSK	200

Table 11-2—LECIM DSSS PHY operating frequency ranges (*continued*)

Band designation	Bandwidth (kHz)	Modulation	Chip rate (kchips/s)
915 MHz	200	BPSK	200
		O-QPSK	400
	400	BPSK	400
		O-QPSK	800
	600	BPSK	600
		O-QPSK	1200
	800	BPSK	800
		O-QPSK	1600
	1000	BPSK	1000
		O-QPSK	2000
922 MHz	200	BPSK	200
		O-QPSK	400
	400	BPSK	400
		O-QPSK	800
	600	BPSK	600
		O-QPSK	1200
	800	BPSK	800
		O-QPSK	1600
	1000	BPSK	1000
		O-QPSK	2000
917 MHz	200	BPSK	200
		O-QPSK	400
	400	BPSK	400
		O-QPSK	800
	600	BPSK	600
		O-QPSK	1200
	800	BPSK	800
		O-QPSK	1600
	1000	BPSK	1000
		O-QPSK	2000

Table 11-2—LECIM DSSS PHY operating frequency ranges (*continued*)

Band designation	Bandwidth (kHz)	Modulation	Chip rate (kchips/s)
920 MHz	200	BPSK	200
		O-QPSK	400
	400	BPSK	400
		O-QPSK	800
	600	BPSK	600
		O-QPSK	1200
	800	BPSK	800
		O-QPSK	1600
	1000	BPSK	1000
		O-QPSK	2000
921 MHz	200	BPSK	200
		O-QPSK	400
	400	BPSK	400
		O-QPSK	800
	600	BPSK	600
		O-QPSK	1200
	800	BPSK	800
		O-QPSK	1600
	1000	BPSK	1000
		O-QPSK	2000
2450 MHz	1000	BPSK	1000
		O-QPSK	2000

The frequency bands for devices supporting the LECIM FSK PHY are shown in Table 11-3, *lecimBaseMultiplier* is defined in 11.1.3.11.3.

The frequency bands for devices supporting the TVWS PHYs are shown in Table 10-47.

Table 11-3—LECIM FSK PHY operating frequency ranges

Band designation	Bandwidth (kHz)	Modulation	Bit rate (kb/s)
169 MHz	25	FSK/ P-FSK	25
	12.5		12.5
	6.25		6.25
	$8 \times lecimBaseMultiplier$	FSK in split mode	$8 \times lecimBaseMultiplier$
	$4 \times lecimBaseMultiplier$		$4 \times lecimBaseMultiplier$
	$2 \times lecimBaseMultiplier$		$2 \times lecimBaseMultiplier$
	<i>lecimBaseMultiplier</i>		<i>lecimBaseMultiplier</i>
262 MHz	12.5	FSK/ P-FSK	12.5
	6.25		6.25
	$4 \times lecimBaseMultiplier$	FSK in split mode	$4 \times lecimBaseMultiplier$
	$2 \times lecimBaseMultiplier$		$2 \times lecimBaseMultiplier$
	<i>lecimBaseMultiplier</i>		<i>lecimBaseMultiplier</i>
433 MHz	37.5	FSK/ P-FSK	37.5
	25		25
	12.5		12.5
	6.25		6.25
	$8 \times lecimBaseMultiplier$	FSK in split mode	$8 \times lecimBaseMultiplier$
	$4 \times lecimBaseMultiplier$		$4 \times lecimBaseMultiplier$
	$2 \times lecimBaseMultiplier$		$2 \times lecimBaseMultiplier$
	<i>lecimBaseMultiplier</i>		<i>lecimBaseMultiplier</i>
470 MHz	37.5	FSK/ P-FSK	37.5
	25		25
	12.5		12.5
	6.25		6.25
	$8 \times lecimBaseMultiplier$	FSK in split mode	$8 \times lecimBaseMultiplier$
	$4 \times lecimBaseMultiplier$		$4 \times lecimBaseMultiplier$
	$2 \times lecimBaseMultiplier$		$2 \times lecimBaseMultiplier$
	<i>lecimBaseMultiplier</i>		<i>lecimBaseMultiplier</i>

Table 11-3—LECIM FSK PHY operating frequency ranges (continued)

Band designation	Bandwidth (kHz)	Modulation	Bit rate (kb/s)
780 MHz	37.5	FSK/ P-FSK	37.5
	25		25
	12.5		12.5
	6.25		6.25
	$8 \times lecimBaseMultiplier$	FSK in split mode	$8 \times lecimBaseMultiplier$
	$4 \times lecimBaseMultiplier$		$4 \times lecimBaseMultiplier$
	$2 \times lecimBaseMultiplier$		$2 \times lecimBaseMultiplier$
	<i>lecimBaseMultiplier</i>		<i>lecimBaseMultiplier</i>
863 MHz	37.5	FSK/ P-FSK	37.5
	25		25
	12.5		12.5
	6.25		6.25
	$8 \times lecimBaseMultiplier$	FSK in split mode	$8 \times lecimBaseMultiplier$
	$4 \times lecimBaseMultiplier$		$4 \times lecimBaseMultiplier$
	$2 \times lecimBaseMultiplier$		$2 \times lecimBaseMultiplier$
	<i>lecimBaseMultiplier</i>		<i>lecimBaseMultiplier</i>
915 MHz	37.5	FSK/ P-FSK	37.5
	25		25
	12.5		12.5
	6.25		6.25
	$8 \times lecimBaseMultiplier$	FSK in split mode	$8 \times lecimBaseMultiplier$
	$4 \times lecimBaseMultiplier$		$4 \times lecimBaseMultiplier$
	$2 \times lecimBaseMultiplier$		$2 \times lecimBaseMultiplier$
	<i>lecimBaseMultiplier</i>		<i>lecimBaseMultiplier</i>
917 MHz	37.5	FSK/ P-FSK	37.5
	25		25
	12.5		12.5
	6.25		6.25
	$8 \times lecimBaseMultiplier$	FSK in split mode	$8 \times lecimBaseMultiplier$
	$4 \times lecimBaseMultiplier$		$4 \times lecimBaseMultiplier$
	$2 \times lecimBaseMultiplier$		$2 \times lecimBaseMultiplier$
	<i>lecimBaseMultiplier</i>		<i>lecimBaseMultiplier</i>

Table 11-3—LECIM FSK PHY operating frequency ranges (continued)

Band designation	Bandwidth (kHz)	Modulation	Bit rate (kb/s)
920 MHz	37.5	FSK/ P-FSK	37.5
	25		25
	12.5		12.5
	6.25		6.25
	$8 \times lecimBaseMultiplier$	FSK in split mode	$8 \times lecimBaseMultiplier$
	$4 \times lecimBaseMultiplier$		$4 \times lecimBaseMultiplier$
	$2 \times lecimBaseMultiplier$		$2 \times lecimBaseMultiplier$
	<i>lecimBaseMultiplier</i>		<i>lecimBaseMultiplier</i>
921 MHz	37.5	FSK/ P-FSK	37.5
	25		25
	12.5		12.5
	6.25		6.25
	$8 \times lecimBaseMultiplier$	FSK in split mode	$8 \times lecimBaseMultiplier$
	$4 \times lecimBaseMultiplier$		$4 \times lecimBaseMultiplier$
	$2 \times lecimBaseMultiplier$		$2 \times lecimBaseMultiplier$
	<i>lecimBaseMultiplier</i>		<i>lecimBaseMultiplier</i>
922 MHz	37.5	FSK/ P-FSK	37.5
	25		25
	12.5		12.5
	6.25		6.25
	$8 \times lecimBaseMultiplier$	FSK in split mode	$8 \times lecimBaseMultiplier$
	$4 \times lecimBaseMultiplier$		$4 \times lecimBaseMultiplier$
	$2 \times lecimBaseMultiplier$		$2 \times lecimBaseMultiplier$
	<i>lecimBaseMultiplier</i>		<i>lecimBaseMultiplier</i>

The frequency bands for devices supporting the RCC PHYs are shown in Table 11-4.

Table 11-4—RCC PHY frequency bands and data rates

Band designation	Modulation and bit rate
161 MHz	LMR GMSK: 9.6/19.2 kb/s LMR 4-FSK: 9.6/19.2/38.4 kb/s LMR QPSK: 16/32 kb/s LMR $\pi/4$ DQPSK: 16/32/36 kb/s
216 MHz	
217 MHz	
220 MHz	
450 MHz	LMR GMSK: 9.6/19.2 kb/s LMR 4-FSK: 9.6/19.2/38.4 kb/s LMR QPSK: 16/32 kb/s LMR $\pi/4$ DQPSK: 16/32/36 kb/s
770 MHz	LMR GMSK: 9.6/19.2 kb/s LMR 4-FSK: 9.6/19.2/38.4 kb/s LMR QPSK: 16/32 kb/s LMR $\pi/4$ DQPSK: 16/32/36 kb/s
800 MHz	
806 MHz	
896 MHz	LMR GMSK: 9.6/19.2 kb/s LMR 4-FSK: 9.6/19.2/38.4 kb/s LMR QPSK: 16/32 kb/s LMR $\pi/4$ DQPSK: 16/32/36 kb/s
915 MHz	LMR GMSK: 9.6/19.2 kb/s LMR 4-FSK: 9.6/19.2/38.4 kb/s LMR QPSK: 16/32 kb/s LMR $\pi/4$ DQPSK: 16/32/36 kb/s LMR DSSS DPSK LMR DSSS BPSK
928 MHz	LMR GMSK: 9.6/19.2 kb/s LMR 4-FSK: 9.6/19.2/38.4 kb/s LMR QPSK: 16/32 kb/s LMR $\pi/4$ DQPSK: 16/32/36 kb/s
2450 MHz	LMR DSSS BPSK
4965 MHz	LMR DSSS DPSK LMR DSSS BPSK
5800 MHz	LMR DSSS DPSK LMR DSSS BPSK

Devices shall start in the PHY mode in which they are instructed to start. If the device is capable of operating in the 868 MHz or 915 MHz bands using one of the optional PHYs described in Clause 13, it shall be able to switch dynamically between the optional PHY and the mandatory BPSK PHY in that band when instructed to do so.

The NITS/CWPAN Part 15.4 specification [B27] also defines operation in the 314–316 MHz and 430–434 MHz bands, which is not described in this standard.

Table 11-5 shows frequency bands for devices supporting the CMB O-QPSK PHY. Table 11-6 shows frequency bands for devices supporting the CMB GFSK PHY.

Table 11-5—CMB O-QPSK PHY frequency bands and data rates

Band identifier (MHz)	Spreading parameters		Data parameters		
	Chip rate (kchip/s)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbol/s)	Symbols
195	1000	O-QPSK	250 (mandatory)	62.5	16-ary orthogonal
	1000	O-QPSK	500 (optional)	125	8-ary orthogonal
416	1000	O-QPSK	250 (mandatory)	62.5	16-ary orthogonal
	1000	O-QPSK	500 (optional)	125	8-ary orthogonal
619	1000	O-QPSK	250 (mandatory)	62.5	16-ary orthogonal
	1000	O-QPSK	500 (optional)	125	8-ary orthogonal

Table 11-6—CMB GRSK PHY frequency bands and data rates

Band identifier (MHz)	Spreading parameters		Data parameters		
	Chip rate (kchip/s)	Modulation	Bit rate (kb/s)	Modulation index	Symbols
195	—	GFSK (mandatory)	50	1.0	Binary
	—	GFSK (optional)	100	0.5 or 1.0	Binary
	—	GFSK (optional)	200	0.5 or 1.0	Binary
416	—	GFSK (mandatory)	50	1.0	Binary
	—	GFSK (optional)	100	0.5 or 1.0	Binary
	—	GFSK (optional)	200	0.5 or 1.0	Binary
619	—	GFSK (mandatory)	50	1.0	Binary
	—	GFSK (optional)	100	0.5 or 1.0	Binary
	—	GFSK (optional)	200	0.5 or 1.0	Binary

A TASK or RS-GFSK PHY compliant device shall be able to support transmission and reception in one or more of the frequency bands defined in Table 11-7.

Table 11-7—TASK and RS-GFSK PHY frequency band definitions

Frequency band identifier	Band designation
0	169 MHz
1	433 MHz
2	450 MHz
3	470 MHz
4	780 MHz
5	863 MHz
6	896 MHz
7	901 MHz
8	915 MHz
9	918 MHz
10	917 MHz
11	928 MHz
12	1427 MHz
13	2450 MHz

11.1.3 Channel assignments

11.1.3.1 Channel information structure

Channel are defined through a channel information structure. This channel information structure is PHY specific and will include, for example, the following information:

- PHY used
- Band used
- Operating mode used (if PHY has different operating modes)
- Actual channel number used

This channel information structure includes all information needed to specify all radio parameters needed to identify a channel.

For each PHY supported, a compliant device shall support all channels allowed by regulations for the region in which the device operates. An exception to this is the HRP UWB PHY where specific mandatory and optional behaviors are as defined in 16.4.1. An additional exception to this is the LRP UWB PHY, in which a transmitter device shall not be required to transmit on more than one channel.

The PHY PIB attributes are described in 12.3.

11.1.3.2 Channel numbering for 780 MHz band

This subclause does not apply to the SUN PHY, RCC PHY, or LECIM PHY specifications. Channels numbered zero to seven are available across the 780 MHz band. The center frequency of these channels is defined as follows:

$$f_c = 780 + 2 k \text{ in megahertz, for } k = 0, \dots, 3$$

$$f_c = 780 + 2 (k - 4) \text{ in megahertz, for } k = 4, \dots, 7$$

where k is the channel number.

11.1.3.3 Channel numbering for 868 MHz, 915 MHz, and 2450 MHz bands

This subclause does not apply to the SUN PHY, LECIM PHY, or MSK PHY specifications. For explanations of channel numbering for the SUN PHYs, LECIM PHYs, and MSK PHYs, see 11.1.3.9, 11.1.3.11, and 11.1.3.7, respectively.

16 channels are available in the 2450 MHz band, 10 in the 915 MHz band, and 1 in the 868 MHz band. The center frequency of these channels is defined as follows:

$$f_c = 868.3 \text{ in megahertz, for } k = 0$$

$$f_c = 906 + 2 (k - 1) \text{ in megahertz, for } k = 1, 2, \dots, 10$$

$$f_c = 2405 + 5 (k - 11) \text{ in megahertz, for } k = 11, 12, \dots, 26$$

where k is the channel number.

Ten channels are available in the 915 MHz band and one in the 868 MHz band. The center frequency of these channels is defined as follows:

$$f_c = 868.3 \text{ in megahertz, for } k = 0$$

$$f_c = 906 + 2 (k - 1) \text{ in megahertz, for } k = 1, 2, \dots, 10$$

where k is the channel number.

11.1.3.4 Channel numbering for CSS PHY

The CSS PHY uses channel numbers defined in Table 11-8. Different subsets of these frequency channels are available in different regions of the world. In North America and Europe, three frequency channels can be selected so that the nonoverlapping frequency channels are used.

Table 11-8—Center frequencies of CSS

Channel number	Frequency (MHz)
0	2412
1	2417
2	2422

Table 11-8—Center frequencies of CSS (*continued*)

Channel number	Frequency (MHz)
3	2427
4	2432
5	2437
6	2442
7	2447
8	2452
9	2457
10	2462
11	2467
12	2472
13	2484

11.1.3.5 Channel numbering for HRP UWB PHY

The HRP UWB PHY uses channel numbers defined in Table 11-9. A compliant HRP UWB device shall be capable of transmitting in at least one of three specified bands, sub-gigahertz, low, or high. An HRP UWB device that implements the sub-gigahertz band shall implement channel 0. An HRP UWB device that implements the low band shall support channel 3. The remaining low-band channels are optional. An HRP UWB device that implements the high band shall support channel 9. The remaining high-band channels are optional.

Table 11-9—HRP UWB PHY channel frequencies

Channel number	Center frequency (MHz)	HRP UWB band/mandatory
0	499.2	Sub-gigahertz
1	3494.4	
2	3993.6	
3	4492.8	Low band
4	3993.6	

Table 11-9—HRP UWB PHY channel frequencies (*continued*)

Channel number	Center frequency (MHz)	HRP UWB band/mandatory
5	6489.6	High band
6	6988.8	
7	6489.6	
8	7488.0	
9	7987.2	
10	8486.4	
11	7987.2	
12	8985.6	
13	9484.8	
14	9984.0	
15	9484.8	

11.1.3.6 Channel numbering for MSK PHY 433 MHz band

The MSK PHY 433 MHz band uses channel numbers defined in Table 11-10. A total of 15 frequency channels are available in the band from 433.05 MHz to 434.79 MHz. Different subsets of these frequency channels are available in different regions of the world. Compliant receivers shall implement all 15 channels in Table 11-10, defaulting to channel 7 unless modified by higher layers.

Table 11-10—MSK PHY 433 MHz band channel frequencies

Channel number	Center frequency (MHz)
0	433.164
1	433.272
2	433.380
3	433.488
4	433.596
5	433.704
6	433.812
7	433.920
8	434.028
9	434.136
10	434.244
11	434.352

Table 11-10—MSK PHY 433 MHz band channel frequencies (continued)

Channel number	Center frequency (MHz)
12	434.460
13	434.568
14	434.676

The multiple narrowband channels for the MSK PHY 433 MHz band are specified in order to improve coexistence with other potential 433 MHz services and to comply with applicable regulations. The selection of specific channels is out of the scope of this standard, being performed by higher layers. Channel selection methodologies might include the following:

- Selecting permanent channels based on an RF survey at the time of system installation
- Performing regular CCAs during operation to dynamically select optimal channels
- Monitoring other link quality metrics to select optimal channels

11.1.3.7 Channel numbering for MSK PHY 2450 MHz band

The MSK PHY 2450 MHz band uses channel numbers defined in Table 11-11 and Table 11-12. A total of 42 frequency channels numbered 15 to 56 are available in the band from 2400 MHz to 2483.5 MHz for the 250 kb/s data rate. A total of 16 frequency channels numbered 57 to 72 are available for the 2000 kb/s data rate. Different subsets of these frequency channels are available in different regions of the world.

Compliant receivers operating at 250 kb/s shall implement all channels in Table 11-11, defaulting to channel 47 unless modified by higher layers. The multiple narrow channels for the narrowband MSK 2450 MHz PHY are specified in order to improve coexistence with other 2450 MHz services. Compliant receivers operating at 2000 kb/s data rate shall implement all channels in Table 11-12 with no default channel. The selection of specific channels is out of the scope of this standard.

Table 11-11—MSK 2450 MHz mandatory PHY channel frequencies for 250 kb/s data rate

Channel number	Center frequency (MHz)
15	2401.75
16	2403.75
17	2405.75
18	2407.75
19	2409.75
20	2411.75
21	2413.75
22	2415.75
23	2417.75
24	2419.75

**Table 11-11—MSK 2450 MHz mandatory PHY channel frequencies
for 250 kb/s data rate (*continued*)**

Channel number	Center frequency (MHz)
25	2421.75
26	2422.5
27	2423.25
28	2425.75
29	2427.75
30	2429.75
31	2431.75
32	2433.75
33	2435.75
34	2437.75
35	2439.75
36	2442
37	2443.75
38	2445.75
39	2447.75
40	2449.75
41	2451.75
42	2453.75
43	2455.75
44	2457.75
45	2459.75
46	2462
47	2463.75
48	2465.75
49	2467.75
50	2469.75
51	2471.75
52	2473.75
53	2475.75
54	2477.75
55	2479.75
56	2481.75

Table 11-12—MSK 2450 MHz mandatory PHY channel frequencies for 2000 kb/s data rate

Channel number	Center frequency (MHz)
57	2405
58	2410
59	2415
60	2420
61	2425
62	2430
63	2435
64	2440
65	2445
66	2450
67	2455
68	2460
69	2465
70	2470
71	2475
72	2480

11.1.3.8 Channel numbering for LRP UWB PHY

The LRP UWB PHY uses channel numbers defined in Table 11-13. A total of ten frequency channels, are available in the 5624.32 MHz to 10 435.2 MHz frequency bands. Different subsets of these frequency channels are available in different regions of the world.

Table 11-13—LRP UWB PHY channel nominal/center frequencies

Channel number	Center frequency (MHz)
0	6489.6
1	6988.8
2	7987.2
3	8486.4
4	6681.6
5	7334.4
6	7987.2

Table 11-13—LRP UWB PHY channel nominal/center frequencies (continued)

Channel number	Center frequency (MHz)
7	8640.0
8	9292.8
9	9945.6

11.1.3.9 Channel numbering for SUN and TVWS PHYs

The channel center frequency ChanCenterFreq for all SUN and TVWS PHYs, except the SUN FSK mode #9, #10, #11, and #12 operating in the 920 MHz band and the SUN O-QPSK PHY operating in the 868–870 MHz band, shall be derived as follows:

$$\text{ChanCenterFreq} = \text{ChanCenterFreq}_0 + \text{NumChan} \times \text{ChanSpacing}$$

where

- ChanCenterFreq_0 is the first channel center frequency
- ChanSpacing is the separation between adjacent channels
- NumChan is the channel number from 0 to $\text{TotalNumChan}-1$
- TotalNumChan is the total number of channels for the available frequency band

The parameters ChanSpacing , TotalNumChan , and ChanCenterFreq_0 for different frequency bands and modulation schemes are specified in Table 11-14.

Table 11-14—Channel numbering for SUN PHYs

Band designation (MHz)	Modulation	ChanSpacing (MHz)	TotalNumChan	ChanCenterFreq ₀ (MHz)
169	SUN FSK operating modes #1, #2, and #3	0.0125	6	169.40625
450	SUN FSK operating modes #1 and #2	0.0125	1599	450.00625
470	SUN FSK operating modes #1, #2, and #3	0.2	199	470.2
	SUN FSK operating mode #1a	0.05	793	470.2
	SUN FSK operating mode #1b	0.1	397	470.2
	SUN OFDM Option 4	0.2	199	470.2
	SUN O-QPSK	0.2	199	470.2

Table 11-14—Channel numbering for SUN PHYs (continued)

Band designation (MHz)	Modulation	ChanSpacing (MHz)	TotalNumChan	ChanCenterFreq₀ (MHz)
780	SUN FSK operating mode #1	0.2	39	779.2
	SUN FSK operating modes #2 and #3	0.4	19	779.4
	SUN FSK operating mode #1a	0.05	153	779.2
	SUN FSK operating mode #1b	0.1	77	779.2
	SUN OFDM Option 4	0.2	39	779.2
	SUN OFDM Option 3	0.4	19	779.4
	SUN OFDM Option 2	0.8	9	779.8
	SUN OFDM Option 1	1.2	6	780.2
	SUN O-QPSK	0.2	39	779.2
	SUN O-QPSK	2	4	780
863	SUN FSK operating modes #1 and #1b	0.1	69	863.1
	SUN FSK operating modes #2 and #3	0.2	35	863.1
	SUN FSK operating mode #1a	0.05	137	863.1
	SUN OFDM Option 4	0.2	35	863.1
	SUN O-QPSK	0.2	35	863.1
866	SUN FSK operating modes #1 and #1b	0.1	29	865.1
	SUN FSK operating modes #2 and #3	0.2	15	865.1
	SUN FSK operating mode #1a	0.05	57	865.1
	SUN OFDM Option 4	0.2	15	865.1
	SUN O-QPSK	0.2	15	865.1

Table 11-14—Channel numbering for SUN PHYs (continued)

Band designation (MHz)	Modulation	ChanSpacing (MHz)	TotalNumChan	ChanCenterFreq₀ (MHz)
867 ^a	SUN FSK operating modes #1 and #1b	0.1	29 (channels 30–58 are used)	863.1 (first frequency used is 866.1)
	SUN FSK operating modes #2 and #3	0.2	15 (channels 15–29 are used)	863.1 (first frequency used is 866.1)
	SUN FSK operating modes #4 and #5	0.4	7 (channels 8–14 are used)	863.2 (first frequency used is 866.4)
	SUN FSK operating mode #1a	0.05	57 (channels 60–116 are used)	863.1 (first frequency is 866.1)
	SUN OFDM Option 4	0.2	15 (channels 15–29 are used)	863.1 (first frequency used is 866.1)
	SUN OFDM Option 3	0.4	7 (channels 8–14 are used)	863.2 (first frequency used is 866.4)
	SUN O-QPSK	0.2	15 (channels 15–29 are used)	863.1 (first frequency used is 866.1)
867	SUN O-QPSK	As defined in Table 11-16		
870	SUN FSK operating modes #1 and #1b	0.1	59	870.1
	SUN FSK operating modes #2 and #3	0.2	29	870.2
	SUN FSK operating mode #1a	0.05	117	870.1
	SUN OFDM Option 4	0.2	29	870.2
	SUN O-QPSK	0.2	29	870.2
896	SUN FSK operating mode #1 ^b	0.0125	399	896.0125
	SUN FSK operating mode #2 ^c	0.0125	397	896.025
	SUN FSK operating mode #3 ^d	0.0125	393	896.05
901	SUN FSK operating mode #1 ^b	0.0125	79	901.0125
	SUN FSK operating mode #2 ^c	0.0125	77	901.025
	SUN FSK operating mode #3 ^d	0.0125	73	901.05

Table 11-14—Channel numbering for SUN PHYs (continued)

Band designation (MHz)	Modulation	<i>ChanSpacing (MHz)</i>	<i>TotalNumChan</i>	<i>ChanCenterFreq₀ (MHz)</i>
915	SUN FSK operating mode #1	0.2	129	902.2
	SUN FSK operating modes #2 and #3	0.4	64	902.4
	SUN FSK operating mode #1a	0.05	513	902.2
	SUN FSK operating mode #1b	0.1	257	902.2
	SUN OFDM Option 4	0.2	129	902.2
	SUN OFDM Option 3	0.4	64	902.4
	SUN OFDM Option 2	0.8	31	902.8
	SUN OFDM Option 1	1.2	20	903.2
	SUN O-QPSK	0.2	129	902.2
	SUN O-QPSK	2	12	904
915-a ^e	SUN FSK operating modes #1, #2, and #3	0.2	129	902.2
	SUN FSK operating modes #4 and #5	0.4	64	902.4
	SUN FSK operating mode #1a	0.05	513	902.2
	SUN FSK operating mode #1b	0.1	257	902.2
	SUN OFDM Option 4	0.2	129	902.2
	SUN OFDM Option 3	0.4	64	902.4
	SUN OFDM Option 2	0.8	31	902.8
	SUN OFDM Option 1	1.2	20	903.2
	SUN O-QPSK	0.2	129	902.2
	SUN O-QPSK	2	12	904

Table 11-14—Channel numbering for SUN PHYs (continued)

Band designation (MHz)	Modulation	ChanSpacing (MHz)	TotalNumChan	ChanCenterFreq₀ (MHz)
915-b ^e	SUN FSK operating modes #1, #2, and #3	0.2	91 (channels 0–26 and 65–128 are used)	902.2
	SUN FSK operating modes #4 and #5	0.4	45 (channels 0–12 and 32–63 are used)	902.4
	SUN FSK operating mode #1a	0.05	358 (channels 0–104 & 260–512 are used)	902.2
	SUN FSK operating mode #1b	0.1	180 (channels 0–52 & 130–256 are used)	902.2
	SUN OFDM Option 4	0.2	91 (channels 0–26 and 65–128 are used)	902.2
	SUN OFDM Option 3	0.4	45 (channels 0–12 and 32–63 are used)	902.4
	SUN OFDM Option 2	0.8	21 (channels 0–5 and 16–30 are used)	902.8
	SUN OFDM Option 1	1.2	13 (channels 0–3 and 11–19 are used)	903.2
	SUN O-QPSK	0.2	91 (channels 26 & 65–128 are used)	902.2
	SUN O-QPSK	2	8 (channels 0, 1, and 6–11 are used)	904

Table 11-14—Channel numbering for SUN PHYs (continued)

Band designation (MHz)	Modulation	ChanSpacing (MHz)	TotalNumChan	ChanCenterFreq₀ (MHz)
915-c ^e	SUN FSK operating modes #1, #2, and #3	0.2	64 (channels 65–128 are used)	902.2 (first frequency used is 915.2)
	SUN FSK operating modes #4 and #5	0.4	32 (channels 32–63 are used)	902.4 (first frequency used is 915.2)
	SUN FSK operating mode #1a	0.05	253 (channels 260–512 are used)	902.2 (first frequency used is 915.2)
	SUN FSK operating mode #1b	0.1	127 (channels 130–256 are used)	902.2 (first frequency used is 915.2)
	SUN OFDM Option 4	0.2	64 (channels 65–128 are used)	902.2 (first frequency used is 915.2)
	SUN OFDM Option 3	0.4	32 (channels 32–63 are used)	902.4 (first frequency used is 915.2)
	SUN OFDM Option 2	0.8	15 (channels 16–30 are used)	902.8 (first frequency used is 915.6)
	SUN OFDM Option 1	1.2	9 (channels 11–19 are used)	903.2 (first frequency used is 916.4)
	SUN O-QPSK	0.2	64 (channels 65–128 are used)	902.2
	SUN O-QPSK	2	6 (channels 6–11 are used)	904 (first frequency used is 916)

Table 11-14—Channel numbering for SUN PHYs (continued)

Band designation (MHz)	Modulation	ChanSpacing (MHz)	TotalNumChan	ChanCenterFreq₀ (MHz)
915-d ^e	SUN FSK operating modes #1, #2, and #3	0.2	29 (channels 65–93 are used)	902.2 (first frequency used is 915.2)
	SUN FSK operating modes #4 and #5	0.4	15 (channels 32–46 are used)	902.4 (first frequency used is 915.2)
	SUN FSK operating mode #1a	0.05	133 (channels 260–372 are used)	902.2 (first frequency used is 915.2)
	SUN FSK operating mode #1b	0.1	57 (channels 130–186 are used)	902.2 (first frequency used is 915.2)
	SUN OFDM Option 4	0.2	29 (channels 65–93 are used)	902.2 (first frequency used is 915.2)
	SUN OFDM Option 3	0.4	15 (channels 32–46 are used)	902.4 (first frequency used is 915.2)
	SUN O-QPSK	0.2	29 (channels 65–93 are used)	902.2 (first frequency used is 915.2)

Table 11-14—Channel numbering for SUN PHYs (continued)

Band designation (MHz)	Modulation	ChanSpacing (MHz)	TotalNumChan	ChanCenterFreq₀ (MHz)
915-e ^e	SUN FSK operating modes #1, #2, and #3	0.2	14 (channels 65–78 are used)	902.2 (first frequency used is 915.2)
	SUN FSK operating modes #4 and #5	0.4	7 (channels 32–38 are used)	902.4 (first frequency used is 915.2)
	SUN FSK operating mode #1a	0.05	53 (channels 260–312 are used)	902.2 (first frequency used is 915.2)
	SUN FSK operating mode #1b	0.1	27 (channels 130–156 are used)	902.2 (first frequency used is 915.2)
	SUN OFDM Option 4	0.2	14 (channels 65–78 are used)	902.2 (first frequency used is 915.2)
	SUN OFDM Option 3	0.4	7 (channels 32–38 are used)	902.4 (first frequency used is 915.2)
	SUN OFDM Option 2	0.8	3 (channels 16–18 are used)	902.8 (first frequency used is 915.6)
	SUN OFDM Option 1	1.2	1 (channel 11 is used)	903.2 (first frequency used is 916.4)
	SUN O-QPSK	0.2	14 (channels 65–78 are used)	902.2 (first frequency used is 915.2)
917	OFDM Option 4	0.2	32	917.1
	OFDM Option 3	0.4	16	917.3
	OFDM Option 2	0.8	8	917.5
	OFDM Option 1	1.2	5	917.9
	SUN FSK operating mode #1	0.2	32	917.1
	SUN FSK operating modes #2 and #3	0.4	16	917.3
	SUN FSK operating mode #1a	0.05	125	917.1
	SUN FSK operating mode #1b	0.1	63	917.1
	SUN O-QPSK	0.2	32	917.1
	SUN O-QPSK	2	3	918.1

Table 11-14—Channel numbering for SUN PHYs (continued)

Band designation (MHz)	Modulation	ChanSpacing (MHz)	TotalNumChan	ChanCenterFreq₀ (MHz)
919 ^e	SUN FSK operating modes #1, #2, and #3	0.2	19 (channels 85–103 are used)	902.2 (first frequency used is 919.2)
	SUN FSK operating modes #4 and #5	0.4	10 (channels 42–51 are used)	902.4 (first frequency used is 919.2)
	SUN FSK operating mode #1a	0.05	73 (channels 340–412 are used)	902.2 (first frequency used is 919.2)
	SUN FSK operating mode #1b	0.1	37 (channels 170–206 are used)	902.2 (first frequency used is 919.2)
	SUN OFDM Option 4	0.2	19 (channels 85–103 are used)	902.2 (first frequency used is 919.2)
	SUN OFDM Option 3	0.4	10 (channels 42–51 are used)	902.4 (first frequency used is 919.2)
	SUN OFDM Option 2	0.8	4 (channels 21–24 are used)	902.8 (first frequency used is 919.6)
	SUN OFDM Option 1	1.2	3 (channels 14–16 are used)	903.2 (first frequency used is 920)
	SUN O-QPSK	0.2	19 (channels 85–103 are used)	902.2 (first frequency used is 919.2)
920	SUN FSK operating mode #1	0.2	38	920.6
	SUN FSK operating modes #2, #5, #6, and #7	0.4	18	920.9
	SUN FSK operating modes #3, #4, and #8	0.6	12	920.8
	SUN FSK operating mode #1a	0.05	149	920.6
	SUN FSK operating mode #1b	0.1	75	920.6
	SUN OFDM Option 4	0.2	38	920.6
	SUN OFDM Option 3	0.4	18	920.9
	SUN OFDM Option 2	0.8	9	921.1
	SUN OFDM Option 1	1.2	5	921.2
	SUN O-QPSK	0.2	37	920.6

Table 11-14—Channel numbering for SUN PHYs (continued)

Band designation (MHz)	Modulation	ChanSpacing (MHz)	TotalNumChan	ChanCenterFreq₀ (MHz)
920-a ^e	SUN FSK operating modes #1, #2, and #3	0.2	20 (channels 92–111 are used)	902.2 (first frequency used is 920.6)
	SUN FSK operating mode #1a	0.05	77 (channels 368–444 are used)	902.2 (first frequency used is 920.6)
	SUN FSK operating mode #1b	0.1	39 (channels 169–207 are used)	902.2 (first frequency used is 920.6)
	SUN OFDM Option 4	0.2	20 (channels 92–111 are used)	902.2 (first frequency used is 920.6)
	SUN O-QPSK	0.2	20 (channels 92–111 are used)	902.2 (first frequency used is 920.6)
920-b ^e	SUN FSK operating modes #1, #2, and #3	0.2	24 (channels 90–113 are used)	902.2 (first frequency used is 920.2)
	SUN FSK operating modes #4 and #5	0.4	12 (channels 45–56 are used)	902.4 (first frequency used is 920.2)
	SUN FSK operating mode #1a	0.05	93 (channels 360–452 are used)	902.2 (first frequency used is 920.2)
	SUN FSK operating mode #1b	0.1	47 (channels 180–226 are used)	902.2 (first frequency used is 920.2)
	SUN OFDM Option 4	0.2	24 (channels 90–113 are used)	902.2 (first frequency used is 920.2)
	SUN OFDM Option 3	0.4	12 (channels 45–56 are used)	902.4 (first frequency used is 920.2)
	SUN OFDM Option 2	0.8	6 (channels 22–27 are used)	902.8 (first frequency used is 920.4)
	SUN OFDM Option 1	1.2	3 (channels 15–17 are used)	903.2 (first frequency used is 921.2)
	SUN O-QPSK	0.2	24 (channels 90–113 are used)	902.2 (first frequency used is 920.2)

Table 11-14—Channel numbering for SUN PHYs (continued)

Band designation (MHz)	Modulation	ChanSpacing (MHz)	TotalNumChan	ChanCenterFreq₀ (MHz)
928	SUN FSK operating mode #1 ^b	0.0125	2559	928.0125
	SUN FSK operating mode #2 ^c	0.0125	2557	928.025
	SUN FSK operating mode #3 ^d	0.0125	2553	928.05
1427	SUN FSK operating mode #1 ^b	0.0125	7279	1427.0125
	SUN FSK operating mode #2 ^c	0.0125	7277	1427.025
	SUN FSK operating mode #3 ^d	0.0125	7273	1427.05
2450	SUN FSK operating mode #1	0.2	416	2400.2
	SUN FSK operating modes #2 and #3	0.4	207	2400.4
	SUN OFDM Option 4	0.2	416	2400.2
	SUN OFDM Option 3	0.4	207	2400.4
	SUN OFDM Option 2	0.8	97	2400.8
	SUN OFDM Option 1	1.2	64	2401.2
	SUN O-QPSK	5	16	2405

^a Channel numbering based on 863–870 MHz numbering.

^b Two adjacent *ChanSpacing*(s) are aggregated to form an overlapping channel with bandwidth of 25 kHz.

^c Four adjacent *ChanSpacing*(s) are aggregated to form an overlapping channel with bandwidth of 50 kHz.

^d Eight adjacent *ChanSpacing*(s) are aggregated to form an overlapping channel with bandwidth of 100 kHz.

^e Channel numbering based on 902–928 MHz numbering.

For the SUN FSK operating mode #9, #10, #11, and #12, 1 MHz channel spacing is used. Overlapping channels are assigned in order to increase the number of available channels represented by the channel separation, which can be narrower than the channel spacing, and which is permitted by Japanese regulation ARIB STD-T108 [B5]. The channel center frequency *ChanCenterFreq* shall be derived as follows:

$$\text{ChanCenterFreq} = \text{ChanCenterFreq}_0 + (\text{NumChan} - \text{FirstNumChan}) \times \text{ChanSeparation}$$

where

ChanCenterFreq₀ is the first channel center frequency for each channel separation

ChanSeparation is the separation between adjacent channels, which is $0.2 \times N$ MHz, where *N* is an integer value from 1 to 5

NumChan is the channel number from

FirstNumChan to *FirstNumChan* + *TotalNumChan* – 1

TotalNumChan is the total number of channels for each channel separation

FirstNumChan is the first channel number for each channel separation

The parameters *ChanSeparation*, *FirstNumChan*, *TotalNumChan*, and *ChanCenterFreq₀* are specified in Table 11-15. The channel assignment specified in this subclause is shown in Annex H.

Table 11-15—Channel numbering parameters for SUN FSK operating mode #9, #10, #11, and #12 in 920 MHz band^a

	<i>ChanSeparation</i> (MHz)	<i>FirstNumChan</i>	<i>TotalNumChan</i>	<i>ChanCenterFreq₀</i> (MHz)
<i>N</i> = 1	0.2	0	34	921.0
<i>N</i> = 2	0.4	34	17	921.0
<i>N</i> = 3	0.6	51	12	921.0
<i>N</i> = 4	0.8	63	9	921.0
<i>N</i> = 5	1.0	72	7	921.0

^a *NumChan* 5, 6, 7, 8, 37, 38, 53, 65, and 73 are not used because of the restriction by Japanese regulation ARIB STD-T108 [B5].

Three channels are available for the SUN O-QPSK PHY operating in the 868–870 MHz band. The channel center frequency for each of these channels is shown in Table 11-16.

Table 11-16—Center frequencies for the SUN O-QPSK PHY operating in the 868–870 MHz band

<i>NumChan</i>	<i>ChanCenterFreq</i> (MHz)
0	868.300
1	868.950
2	869.525

In the case of TVWS PHYs, *ChanCenterFreq₀* is derived as follows:

$$\text{ChanCenterFreq}_0 = \text{macStartBandEdge} + \text{ChanSpacing}$$

TotalNumChan is derived as follows:

$$\text{TotalNumChan} = \text{floor}((\text{macEndBandEdge} - \text{macStartBandEdge}) / \text{ChanSpacing} - 1)$$

macStartBandEdge and *macEndBandEdge* are set by the higher layers, appropriate for the band of operation at a particular time.

11.1.3.10 Channel numbering for 2380 MHz band

15 channels numbered zero to fourteen are available across the 2380 MHz band. The center frequencies of these channels are defined as follows:

$$f_c = 2363 + 5 k \text{ in megahertz, for } k = 0, 1, \dots, 6$$

$$f_c = 2367 + 5 (k - 7) \text{ in megahertz, for } k = 7, 8, \dots, 13$$

$$f_c = 2395 \text{ in megahertz, for } k = 14$$

where k is the channel number.

11.1.3.11 Channel numbering for LECIM PHYs

11.1.3.11.1 General

For the 2.4 GHz band, a device shall support all the channels from the lowest to the highest channels (inclusive) indicated in the LECIM Capabilities IE, as described in 10.15.2.2.

11.1.3.11.2 Channel numbering for LECIM DSSS PHY

When *phyLecimCurrentPhyType* is set to DSSS, the channel plan is described as follows. The channel center frequency, *ChanCenterFreq*, for all LECIM DSSS PHY frequency bands shall be derived as follows:

$$\text{ChanCenterFreq} = \text{FreqBandEdge} + \text{FreqOffset} + (\text{NumChan} - 1) \times \text{ChanSpacing}$$

where

<i>ChanCenterFreq</i>	is the channel center frequency
<i>FreqBandEdge</i>	is the band edge for the frequency band in use (<i>phyLecimCurrentBand</i>)
<i>FreqOffset</i>	is the frequency offset for each band
<i>NumChan</i>	is the designated channel identifier number from 1 to N
<i>ChanSpacing</i>	is the separation between adjacent channels (<i>phyLecimChannelSpacing</i>)

The parameters *FreqBandEdge*, *FreqOffset*, *ChanSpacing*, and the range of valid *NumChan* channel numbers for each frequency band are listed in Table 11-17.

Table 11-17—Frequency band, frequency band offset, and channel spacing for LECIM DSSS PHY

Band designation	<i>FreqBandEdge</i> (MHz)	<i>FreqOffset</i> (MHz)	<i>ChanSpacing</i> (MHz)	<i>NumChan</i> range
433 MHz	433	0.17	0.1	1–16
	433	0.22	0.2	1–8
470 MHz	470	0.2	0.2	1–199
780 MHz	779	0.2	0.2	1–39
863 MHz	863	0.075	0.1	1–69
	863	0.125	0.2	1–34

Table 11-17—Frequency band, frequency band offset, and channel spacing for LECIM DSSS PHY (continued)

Band designation	<i>FreqBandEdge</i> (MHz)	<i>FreqOffset</i> (MHz)	<i>ChanSpacing</i> (MHz)	<i>NumChan</i> range
915 MHz	902	0.2	0.2	1–129
917 MHz	917	0.1	0.2	1–32
920 MHz	920	0.6	0.2	1–36
921 MHz	921	0.2	0.2	1–34
922 MHz	915	0.2	0.2	1–64
2450 MHz	2400	0.2	0.2	1–416

11.1.3.11.3 Channel numbering for LECIM FSK PHY

When *phyLecimCurrentPhyType* is set to FSK, the channel center frequency *ChanCenterFreq* for the LECIM FSK PHY shall be derived as follows:

$$\text{ChanCenterFreq} = \text{ChanSpacing} \times \text{NumChan} + \text{ChanCenterFreq}_0$$

where

- ChanSpacing* is the separation between adjacent channels (*phyLecimChannelSpacing*)
- NumChan* is the current channel number occurring in the range of 0 to *TotalNumChan* – 1
- TotalNumChan* is the total number of channels for the available frequency band
- ChanCenterFreq*₀ is the first channel center frequency of the band in use (*phyLecimCurrentBand*)

Parameters *TotalNumChan* and *ChanCenterFreq*₀ are specified in Table 11-18, Table 11-19, Table 11-20, Table 11-21, Table 11-22, Table 11-23, and Table 11-24 for different frequency bands and channel spacings.

The parameter *lecimBaseMultiplier* is given by: $26\ 000 \times \frac{3}{2^{15}} = 2.38037109375$

For band designation 169 MHz, *ChanCenterFreq*₀ shall be 169.4375 MHz and *TotalNumChan* shall be one.

Table 11-18—*TotalNumChan* and *ChanCenterFreq*₀ when *ChanSpacing* = 200 kHz

Band designation	<i>TotalNumChan</i>	<i>ChanCenterFreq</i> ₀ (MHz)
433 MHz	8	433.22
470 MHz	199	470.2
780 MHz	39	779.2
863 MHz	34	863.125
915 MHz	129	902.2
917 MHz	32	917.1

**Table 11-18—*TotalNumChan* and *ChanCenterFreq₀* when
ChanSpacing = 200 kHz (continued)**

Band designation	<i>TotalNumChan</i>	<i>ChanCenterFreq₀</i> (MHz)
920 MHz	36	920.6
921 MHz	34	921.2
922 MHz	64	915.2

**Table 11-19—*TotalNumChan* and *ChanCenterFreq₀* when
ChanSpacing = 100 kHz**

Band designation	<i>TotalNumChan</i>	<i>ChanCenterFreq₀</i> (MHz)
433 MHz	16	433.170
470 MHz	399	470.1
780 MHz	79	779.1
863 MHz	69	863.075
915 MHz	259	902.1
921 MHz	69	921.1
922 MHz	129	915.1

**Table 11-20—*TotalNumChan* and *ChanCenterFreq₀* when
ChanSpacing = 12.5 kHz**

Band designation	<i>TotalNumChan</i>	<i>ChanCenterFreq₀</i> (MHz)
262 MHz	156	262.03125

**Table 11-21—*TotalNumChan* and *ChanCenterFreq₀* when
ChanSpacing = *lecmBaseMultiplier* kHz**

Band designation	<i>TotalNumChan</i>	<i>ChanCenterFreq₀</i> (MHz)
169 MHz	28	169.4045797
262 MHz	835	262.0064702
433 MHz	723	433.059886
470 MHz	16 795	470.0113902
780 MHz	3 347	779.0169302
863 MHz	2 926	863.0185902

**Table 11-21—*TotalNumChan* and *ChanCenterFreq₀* when
ChanSpacing = *lecmBaseMultiplier* kHz (continued)**

Band designation	<i>TotalNumChan</i>	<i>ChanCenterFreq₀</i> (MHz)
915 MHz	10 907	902.0197502
917 MHz	2 715	917.0196602
920 MHz	3 345	920.0197502
921 MHz	2 925	921.0197502
922 MHz	5 445	915.0197502

**Table 11-22—*TotalNumChan* and *ChanCenterFreq₀* when
ChanSpacing = 2 × *lecmBaseMultiplier* kHz**

Band designation	<i>TotalNumChan</i>	<i>ChanCenterFreq₀</i> (MHz)
169 MHz	14	169.4057699
262 MHz	417	262.0076604
433 MHz	361	433.0610762
470 MHz	8397	470.0125804
780 MHz	1673	779.0181204
863 MHz	1463	863.0197804
915 MHz	5453	902.0209404
917 MHz	1357	917.0208504
920 MHz	1672	920.0209404
921 MHz	1462	921.0209404
922 MHz	2722	915.0209404

**Table 11-23—*TotalNumChan* and *ChanCenterFreq₀* when
ChanSpacing = 4 × *lecmBaseMultiplier* kHz**

Band designation	<i>TotalNumChan</i>	<i>ChanCenterFreq₀</i> (MHz)
169 MHz	7	169.4081502
262 MHz	208	262.0100407
433 MHz	180	433.0634565
470 MHz	4198	470.0149607
780 MHz	836	779.0205007
863 MHz	731	863.0221607

Table 11-23—*TotalNumChan* and *ChanCenterFreq₀* when *ChanSpacing* = 4 × *lecimBaseMultiplier* kHz (continued)

Band designation	<i>TotalNumChan</i>	<i>ChanCenterFreq₀</i> (MHz)
915 MHz	2726	902.0233207
917 MHz	678	917.0232307
920 MHz	836	920.0233207
921 MHz	731	921.0233207
922 MHz	1361	915.0233207

Table 11-24—*TotalNumChan* and *ChanCenterFreq₀* when *ChanSpacing* = 8 × *lecimBaseMultiplier* kHz

Band designation	<i>TotalNumChan</i>	<i>ChanCenterFreq₀</i> (MHz)
169 MHz	3	169.412911
262 MHz	104	262.0148015
433 MHz	90	433.0682173
470 MHz	2099	470.0197215
780 MHz	418	779.0252615
863 MHz	365	863.0269215
915 MHz	1363	902.0280815
917 MHz	339	917.0279915
920 MHz	418	920.0280815
921 MHz	365	921.0280815
922 MHz	680	915.0280815

11.1.3.12 Channel numbering for RCC PHYs

Applicable regulations shall be used to define channel numbering where indicated in Table 11-25. For all other bands, the channel center frequency, *ChanCenterFreq*, for an RCC PHY shall be derived as follows:

$$\text{ChanCenterFreq} = \text{ChanCenterFreq}_0 + \text{NumChan} \times \text{ChanSpacing}$$

where

- ChanCenterFreq₀* is the first channel center frequency
- ChanSpacing* is the separation between adjacent channels
- NumChan* is the channel number from 0 to *TotalNumChan* – 1
- TotalNumChan* is the total number of channels for the available frequency band

The parameters *ChanSpacing*, *TotalNumChan*, and *ChanCenterFreq₀* for each frequency band are specified in Table 11-25. The information in Table 11-25 the applies to all RCC modulation schemes.

Table 11-25—RCC PHY channel numbering information

Band designation	<i>ChanSpacing</i> (MHz)	<i>TotalNumChan</i>	<i>ChanCenterFreq₀</i> (MHz)
161 MHz	0.0075	187	160.1775
216 MHz	0.00625	159	216.00625
217 MHz	0.00625	479	217.00625
220 MHz	0.005	400	220.0025
450 MHz	0.00625	3199	450.00625
770 MHz	0.00625	960	769.003125
800 MHz	0.00625	960	799.003125
806 MHz	As defined in 47 CFR, Part 90, Subpart S, Section 90.613		
896 MHz	As defined in 47 CFR, Part 90, Subpart S, Section 90.613		
915 MHz	0.500	51	902.500
928 MHz	0.00625	5119	928.0125
2450 MHz	0.2	416	2400.2
4965 MHz	As defined in 47 CFR, Part 90, Subpart Y, Section 90.1213		
5800 MHz	0.5	249	5725.5

11.1.3.13 Channel numbering for CMB PHYs

11.1.3.13.1 General

Channel center frequency of CMB PHYs is specified as:

$$\text{ChanCenterFreq} = \text{FreqBandEdge} + \text{ChanSpacing} \times (\text{NumChan} + 0.5)$$

where

- ChanCenterFreq* is the operational channel center frequency
- FreqBandEdge* is the band edge for the frequency band as specified in 11.1.3.13.2 and 11.1.3.13.3
- NumChan* is the designated channel identifier number as specified in 11.1.3.13.2 and 11.1.3.13.3
- ChanSpacing* is the separation between adjacent channels as specified in 11.1.3.13.2 and 11.1.3.13.3

11.1.3.13.2 Channel numbering for CMB O-QPSK PHY

The parameters *FreqBandEdge* and *NumChan* and the valid range of *ChanSpacing* for CMB GFSK PHY are listed in Table 11-26.

Table 11-26—Band edge, channel identifier, and channel spacing for CMB O-QPSK PHY

Band identifier (MHz)	<i>FreqBandEdge</i> (MHz)	<i>NumChan</i>	<i>ChanSpacing</i> (MHz)
195	174	0–20	2
416	407	0–8	2
619	608	0–10	2

11.1.3.13.3 Channel numbering for CMB GFSK PHY

The parameters *FreqBandEdge* and *NumChan* and the valid range of *ChanSpacing* for CMB GFSK PHY are listed in Table 11-27.

Table 11-27—Band edge, channel identifier, and channel spacing for CMB GFSK PHY

Band identifier (MHz)	<i>FreqBandEdge</i> (MHz)	<i>NumChan</i>	<i>ChanSpacing</i> (MHz)
195	174	0–83	0.5
416	407	0–5	0.5
619	608	0–43	0.5

11.1.3.14 Channel numbering for TASK and RS-GFSK PHYs

The channel center frequency for TASK and RS-GFSK PHYs shall be derived as follows:

$$\text{ChanCenterFreq} = \text{ChanCenterFreq}_0 + \text{NumChan} \times \text{ChanSpacing}$$

where

*ChanCenterFreq*₀ is the first channel center frequency

ChanSpacing is the separation between two adjacent channels

NumChan is the channel number from 0 to *TotalNumChan* – 1

TotalNumChan is the total number of channels for the available frequency band

The parameters *ChanSpacing*, *TotalNumChan*, and *ChanCenterFreq*₀ for different frequency bands for TASK are specified in Table 11-28. The parameters *ChanSpacing*, *TotalNumChan*, and *ChanCenterFreq*₀ for different frequency bands and MCS levels for RS-GFSK are specified in Table 11-29. The MCS levels for RS-GFSK PHY are numbered as described in Table 32-2 and Table 32-3.

For specifics of the MCS modes as shown in Table 11-29, see Table 32-2 and Table 32-3.

Table 11-28—Total number of channels and first channel center frequencies for TASK PHYs

Frequency band identifier	<i>ChanSpacing</i> (MHz)	<i>TotalNumChan</i>	<i>ChanCenterFreq₀</i> (MHz)
1	0.4	4	433.3
3	0.8	50	470.4
4	2	4	780
5	2	6	864
8	2	10	906
13	5	16	2405

Table 11-29—Total number of channels and first channel center frequencies for RS-GFSK PHYs

Band designation (MHz)	MCS mode	<i>ChanSpacing</i> (MHz)	<i>TotalNumChan</i>	<i>ChanCenterFreq₀</i> (MHz)
169	0, 0a	0.0125	6	169.40625
	1, 1a	0.025	3	169.4125
433	0, 0a	0.0125	139	433.0625
	1, 1a	0.025	69	433.075
	2, 2a	0.2	8	433.25
450	0, 0a	0.0125	1600	450.00625
	1, 1a	0.025	800	450.0125
	2, 2a	0.2	100	450.100
	3, 3a	0.4	50	450.200
	4, 4a, 6	1.0	20	450.500
	5	0.5	40	450.250
	7	2.0	10	451.000
470	1, 1a	0.025	1600	470.025
	2, 2a	0.2	200	470.2
	3, 3a	0.4	100	470.4
	4, 4a, 6	1.0	40	471.0
	5	0.5	80	470.5
	7	2.0	20	472.0

Table 11-29—Total number of channels and first channel center frequencies for RS-GFSK PHYs (continued)

Band designation (MHz)	MCS mode	ChanSpacing (MHz)	TotalNumChan	ChanCenterFreq₀ (MHz)
780	2, 2a	0.2	40	779.2
	3, 3a	0.4	20	779.4
	4, 4a, 6	1.0	8	780.0
	5	0.5	16	779.5
863 and 870	2, 2a	0.2	65	863.125
	3, 3a	0.4	32	863.225
	4, 4a, 6	1.0	13	864.0
	5	0.5	26	863.5
	7	2.0	6	865.0
896	0, 0a	0.0125	400	896.0125
	1, 1a	0.025	200	896.025
	5	0.5	10	896.5
901	0, 0a	0.0125	80	901.0125
	1, 1a	0.025	20	901.025
915	2, 2a	0.2	130	902.2
	3, 3a	0.4	65	902.4
	4, 4a, 6	1.0	25	903.0
	5	0.5	52	902.5
	7	2.0	13	904.0
916	2, 2a, 3, 3a, 4, 4a, 5, 6, 7	0.1	121	916.0
917	2, 2a	0.2	33	917.1
	3, 3a	0.4	16	917.3
	5	0.5	13	917.5
928	0, 0a, 1, 1a	0.2	160	928.0125
1427	0, 0a, 1, 1a	0.2	455	1427.0125
2450	2, 2a	0.2	417	2400.2
	3, 3a	0.4	208	2400.4
	4, 4a, 6	1.0	83	2401.0
	5	0.5	167	2400.5
	7	2.0	41	2402.0

11.1.4 Minimum LIFS and SIFS periods

For all PHYs other than the HRP UWB PHY, RCC PHY, and SUN OFDM PHY, the minimum LIFS period and SIFS period are as follows:

- *macLifsPeriod*: 40 symbols
- *macSifsPeriod*: 12 symbols

For the HRP UWB PHY, the minimum LIFS period and SIFS period are as follows:

- *macLifsPeriod*: 40 preamble symbols
- *macSifsPeriod*: 12 preamble symbols

For the HRP UWB PHY, the actual time for *macLifsPeriod* and *macSifsPeriod* depends on the pulse repetition frequency (PRF) and channel in use, as described in Table 16-6.

For the RCC PHY, the minimum LIFS period and SIFS period are as follows:

- *macLifsPeriod*: 5 symbols
- *macSifsPeriod*: 5 symbols

For the SUN OFDM PHY, the MAC symbol period is defined in 20.1.

11.1.5 RF power measurement

Unless otherwise stated, all RF power measurements, either transmit or receive, shall be made at the appropriate transceiver to antenna connector. The measurements shall be made with equipment that is either matched to the impedance of the antenna connector or corrected for any mismatch. For devices without an antenna connector, the measurements shall be interpreted as EIRP, and any radiated measurements shall be corrected to compensate for the antenna gain in the implementation.

11.1.6 Transmit power

A compliant device shall have its nominal transmit power level that is allowed in the network and the currently configured upper bound based on that level indicated by the PHY parameters, *phyMaxTxPower* and *phyTxPower*, respectively as defined in 12.3.2.

11.1.7 Out-of-band spurious emission

The out-of-band spurious emissions shall conform with applicable regulations.

11.1.8 Receiver sensitivity definitions

The general conditions for measuring receiver sensitivity are defined in Table 11-30.

Table 11-30—Receiver sensitivity conditions

Term	Definition of term	Conditions
Packet error rate (PER)	Average fraction of transmitted packets that are not correctly received.	Average measured over random PSDU data.
Receiver sensitivity	Lowest input power for which the PER conditions are met.	PSDU length = 250 octets for SUN PHYs with data rates 50 kb/s and greater, 20 octets for all other PHYs. PER < 10% for SUN PHYs. PER < 1% for all other PHYs. Power measured at antenna terminals with interference not present.

11.1.9 Common signaling mode (CSM) for SUN PHY

The CSM is a common PHY mode specified to facilitate the MPM scheme described in 10.9. A SUN device acting as a coordinator and with a duty cycle greater than 1% shall support CSM. The specification of CSM is given in Table 11-31. The modulation and channel specification of CSM are given in 20.3.

Table 11-31—PHY specification of the CSM for MPM scheme

Band designation	Modulation	Modulation index	Channel spacing	Data rate
470 MHz				
780 MHz				
863 MHz				
915 MHz	2-FSK	1	200 kHz	50 kb/s
917 MHz				
920 MHz				
2450 MHz				

The value of the SFD field, as described in 20.2.2.3, for CSM shall be that associated with a value of zero for the PIB attribute *phySunFskSfd*, as defined in 12.3.11.

11.2 General radio specifications

11.2.1 General

For the SUN FSK PHY, SUN OFDM PHY, and SUN O-QPSK PHY, the meaning of a symbol period for timing parameters is described in 6.2.

11.2.2 TX-to-RX turnaround time

The TX-to-RX turnaround time shall be less than or equal to *aTurnaroundTime*, as defined in Table 12-1.

The TX-to-RX turnaround time is defined as the time at the air interface from the trailing edge of the last part/chip (of the last symbol) of a transmitted PPDU to the time that the PHY is ready to receive the leading edge of the first part/chip (of the first symbol) of the next received PPDU.

11.2.3 RX-to-TX turnaround time

The RX-to-TX turnaround time shall be less than or equal to *aTurnaroundTime*, as defined in Table 12-1.

The RX-to-TX turnaround time is defined as the time at the air interface from the trailing edge of the last chip (of the last symbol) of a received PPDU to the time that the PHY transmits the leading edge of the first chip (of the first symbol) of the next transmitted PPDU.

11.2.4 Error-vector magnitude (EVM) definition

The modulation accuracy of the transmitter is determined with an EVM measurement. In order to calculate the EVM, a time record of N received complex chip values $(\tilde{I}_j, \tilde{Q}_j)$ is captured. For each received complex chip, a decision is made about which complex chip value was transmitted. The ideal position of the chosen complex chip (the center of the decision box) is represented by the vector (I_j, Q_j) . The error vector $(\delta I_j, \delta Q_j)$ is defined as the distance from this ideal position to the actual position of the received point, as illustrated in Figure 11-1.

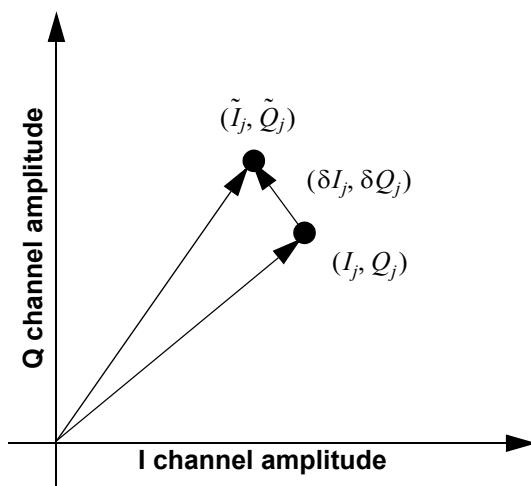


Figure 11-1—Error-vector calculation

Thus, the received vector is the sum of the ideal vector and the error vector as follows:

$$(\tilde{I}_j, \tilde{Q}_j) = (I_j, Q_j) + (\delta I_j, \delta Q_j)$$

The EVM is defined as follows:

$$\text{EVM} \equiv \sqrt{\frac{\frac{1}{N} \sum_{j=1}^N (\delta I_j^2 + \delta Q_j^2)}{S^2}} \times 100\%$$

where

S is the magnitude of the vector to the ideal constellation point

$(\delta I_j, \delta Q_j)$ is the error vector

The error-vector measurement shall be made on baseband I and Q chips after recovery through a reference receiver system. The reference receiver shall perform carrier lock, symbol timing recovery, and amplitude adjustment while making the measurements.

11.2.5 Receiver maximum input level of desired signal

The receiver maximum input level is the maximum power level of the desired signal present at the input of the receiver for which the error rate criterion in 11.1.8 is met.

11.2.6 Receiver ED

The receiver ED measurement is intended for use by a network layer as part of a channel selection algorithm. It is an estimate of the received signal power within the bandwidth of the channel. No attempt is made to identify or decode signals on the channel. The ED measurement time, to average over, shall be equal to eight symbol periods, unless the PHY specifies shorter *phyCcaDuration* time, in which case it is used instead.

The ED result shall be reported to the next higher layer using the MLME-SCAN.confirm primitive. The minimum ED value (zero) shall indicate received power less than 10 dB above the lowest specified receiver sensitivity, in dBm, for the PHY. The range of received power spanned by the ED values shall be at least 40 dB. Within this range, the mapping from the received power in decibels to ED value shall be linear with an accuracy of ± 6 dB.

11.2.7 Link quality indicator (LQI)

The LQI measurement is a characterization of the strength and/or quality of a received packet. The measurement may be implemented using receiver ED, a signal-to-noise ratio estimation, or a combination of these methods. The use of the LQI result by the network or application layers is not specified in this standard.

The LQI measurement shall be performed for each received packet. The minimum and maximum LQI values (0x00 and 0xff) should be associated with the lowest and highest quality compliant signals detectable by the receiver, and LQI values in between should be uniformly distributed between these two limits. At least eight unique values of LQI shall be used.

11.2.8 Clear channel assessment (CCA)

With the exception of the HRP UWB PHY, a compliant PHY shall provide the capability to perform CCA according to at least one of the following methods:

- *CCA Mode 1: Energy above threshold.* CCA shall report a busy medium upon detecting any energy above the ED threshold.
- *CCA Mode 2: Carrier sense only.* CCA shall report a busy medium only upon the detection of a signal compliant with this standard with the same modulation and spreading characteristics of the PHY that is currently in use by the device.
- *CCA Mode 3:* one of following:
 - *CCA Mode 3a: Carrier sense with energy above threshold when either is required.* CCA shall report a busy medium if either CCA Mode 1 or CCA Mode 2 would return busy.
 - *CCA Mode 3b: Carrier sense with energy above threshold when both are required.* CCA shall report a busy medium only if both CCA Mode 1 and CCA Mode 2 would return busy.
- *CCA Mode 4: ALOHA.* CCA shall always report an idle medium.

An HRP UWB PHY shall implement one of CCA Mode 1 through CCA Mode 4 or one of the following methods:

- *CCA Mode 5: HRP UWB preamble sense based on the SHR of a frame.* In this mode, the CCA shall operate to detect the UWB preamble as specified in 16.2.6 and selected by the *phyCurrentCode*. The device shall spend at least its normal operational preamble detection time looking for this preamble before reporting an idle medium in the case where no preamble is detected. In the case where the preamble is detected, the CCA shall report a busy medium, and thereafter, shall not report an idle medium until a period has elapsed that is not shorter than the time required at the current network operational data rate and PSR, (e.g., as specified by the DataRate and UwbPreambleSymbolRepetitions parameters of the MCPS-DATA.request), to complete the transmission of a frame of 127 octets, or 1023 octets for the HRP-ERDEV in the HPRF mode, and to receive its acknowledgment.
- *CCA Mode 6: HRP UWB preamble sense based on the packet with the multiplexed preamble as specified in 16.6.* CCA shall report a busy medium upon detection of a preamble symbol as specified in 16.2.6.

For any of the CCA modes, if a request to perform CCA is received by the PHY during reception of a PPDU, CCA shall report a busy medium. PPDU reception is considered to be in progress following detection of the SFD, and it remains in progress until the number of octets specified by the decoded PHR has been received.

NOTE 1—These modes are used to provide cooperative utilization of the medium in an IEEE 802.15.4 network. They are not designed to provide regulatory compliance, and in some cases only a subset of these modes may meet regulatory requirements.

As an example, EN 300 328 V2.2.2 requires energy detect for a minimum of 18 μ s. In this case an implementer could choose to use CCA mode 3a within the CSMA-CA algorithm, using *phyCcaDuration* set to 18 μ s or greater to achieve the behavior described in the reference. Implementing a design in this manner would provide an optimized network that would not be disadvantaged in a mixed protocol environment with networks other than IEEE 802.15.4.

The PHY PIB attribute *phyCcaMode*, as described in 12.3.2, shall indicate the appropriate operation mode. The CCA parameters are subject to the following criteria:

- a) Unless otherwise specified in this standard for the PHY being used, the ED threshold shall be *phyCcaEdThreshold*.
- b) The CCA detection time shall be equal to *phyCcaDuration*, as defined in Table 12-2.
- c) For SUN FSK PHY, when operating with channel spacing that is less than twice the symbol rate, use of CCA Mode 1 and CCA Mode 3 is not recommended.
- d) For SUN OFDM the ED threshold shall be at most $-75 + 10 \times \log_{10}(\text{BW}/10^6)$ in dBm and BW in hertz, where BW is the nominal bandwidth as specified in Table 21-10.

NOTE 2—The required ED threshold is sometimes specified by local regulations for a given band, and varies region to region and band to band.

11.3 Ranging capable PHY

11.3.1 General

This subclause applies for devices that have implemented ranging support (RDEVs).

11.3.2 Distance commitment on PSDU

Distance commitment on data is a decoding method that only captures the energy during short active RF periods within each symbol of the PSDU. The position of the short active period within a symbol duration is

selected from information of the channel obtained during the preamble such that the earliest path(s) are captured. Figure 11-2 illustrates the distance commitment principle.

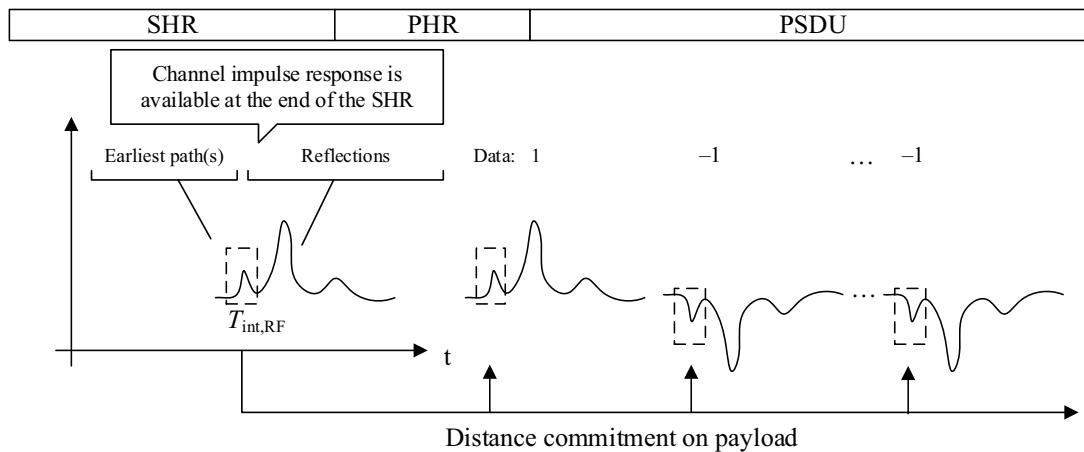


Figure 11-2—Distance commitment principle and RF integration window

Distance commitment can be used by ranging capable PHYs that implement channel sounding and are able to provide channel state information (amplitude and/or phase in the time domain) after the SHR and before the processing of the PSDU symbols. The time of arrival of the earliest detected leading edge of the received signal can be extracted from the channel state information available as described in 7.1.1.4 of “Application of IEEE Std 802.15.4” [B4].

Under distance commitment operation at the receiver, the time of arrival and the energy integration window $T_{int,RF}$ shall be used for PSDU symbol decoding. The aperture $T_{int,RF}$ is the allowed window duration for collecting and integrating the incoming RF energy at the receiver. Distance commitment provides for symbols of the PSDU are decoded at the measured distance corresponding to the time of arrival of the earliest detected leading edge with maximum PSDU symbol distance offset from RMARKER provided in Table 11-32. Relevant implementation guidelines are provided in Section 2 of “Authenticated Ranging of IEEE 802.15.4” [B6].

Table 11-32—Distance commitment level definition for authenticated ranging

DistanceCommitmentLevel	$T_{int,RF}$ aperture time (RSTU)	Maximum PSDU symbol distance offset from RMARKER ($c_0 = \text{speed of light}$)
DCL_1_4096	1/4096	$c_0 \times 1/4096$
DCL_1_2048	1/2048	$c_0 \times 1/2048$
DCL_1_1024	1/1024	$c_0 \times 1/1024$
DCL_1_512	1/512	$c_0 \times 1/512$
DCL_1_256	1/256	$c_0 \times 1/256$
DCL_1_128	1/128	$c_0 \times 1/128$
DCL_1_64	1/64	$c_0 \times 1/64$
DCL_DISABLED	N/A	N/A

NOTE—Although Figure 11-2 shows a phase inversion modulation, practical implementations can apply this technique with other modulation schemes, (e.g., the PBFSK modulation of the LRP UWB PHY).

The MCPS-RANGING-VERIFIER and MCPS-RANGING-PROVER primitives include the DistanceCommitmentLevel parameter to set the value of the aperture $T_{\text{int},\text{RF}}$.

12. PHY services

12.1 Overview

The PHY provides an interface between the MAC sublayer and the physical radio channel, via the RF firmware and the RF hardware. The PHY conceptually includes a management entity called the PLME. This entity provides the layer management service interfaces through which layer management functions may be invoked. The physical layer management entity (PLME) is also responsible for maintaining a database of managed objects pertaining to the PHY. This database is referred to as the PHY PAN information base (PIB).

Figure 12-1 depicts the components and interfaces of the PHY.

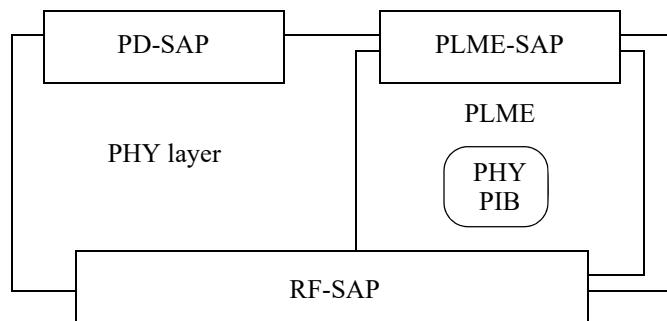


Figure 12-1—PHY reference model

The PHY provides two services, accessed through two SAPs: the PHY data service, accessed through the PHY data SAP (PD-SAP), and the PHY management service, accessed through the physical layer management entity service access point (PLME-SAP). The PD-SAP and PLME-SAP are not defined in this standard as they are not expected to be exposed in a typical implementation. The PHY PIB attributes are accessed through the MLME-SAP with the MLME-GET and MLME-SET primitives.

Constants and attributes that are specified and maintained by the PHY are written in italics. Constants have a general prefix of “a”, for example *aTurnaroundTime*, and are listed in Table 12-1. Attributes have a general prefix of “phy”, for example *phyCurrentChannelInfo*, and are listed in tables 12.3.

Attributes that have a prefix of “phyHrpUwb”, for example *phyHrpUwbDataRatesSupported*, apply only to the HRP UWB PHY and are not used for other PHYs.

12.2 PHY constants

The constants that define the characteristics of the PHY are presented in Table 12-1. These constants are hardware dependent and cannot be changed during operation.

Table 12-1—PHY constants

Constant	Description	Value
<i>aLeipDelayTime</i>	The delay between the start of the SFD and the LEIP, as described in 19.6.	0.815 ms
<i>aTurnaroundTime</i>	RX-to-TX or TX-to-RX turnaround time (in symbol periods), as defined in 11.2.2 and 11.2.3.	For the SUN, RS-GFSK, TVWS, and LECIM FSK PHYs, the value is 1 ms expressed in symbol periods, rounded up to the next integer number of symbol periods using the ceiling() function. ^a For the LECIM DSSS PHY, the value is 1 ms expressed in modulation symbol periods, rounded up to the next integer number of symbol periods using the ceiling() function. For the MSK PHY with a data rate of 2000 kb/s, the value is 384 symbol periods. The value is 12 for all other PHYs.

^a The function ceiling() returns the smallest integer value greater than or equal to its argument value.

12.3 PHY PIB attributes

12.3.1 Overview

The PHY PIB includes the attributes required to manage the PHY of a device. Attributes marked with a dagger (†) are read-only attributes (i.e., attribute can only be set by the PHY), which can be read by the next higher layer using the MLME-GET.request primitive. All other attributes can be read or written by the next higher layer using the MLME-GET.request or MLME-SET.request primitives, respectively.

12.3.2 Generic PHY PIB attributes

Generic PHY PIB attributes are presented in Table 12-2 and Table 12-3 describes the *phyPeersTxPower* entries.

Table 12-2—Generic PHY PIB attributes

Attribute	Type	Range	Description
<i>phyBroadcastTxPower</i>	Signed integer	—	Transmit power in dBm while broadcasting. This value is managed by an upper layer but shall be lower or equal to <i>phyTxPower</i> .
<i>phyCcaDuration</i>	Integer	1–1000000	The duration for CCA, specified in microseconds. If a recommended <i>phyCcaDuration</i> is not specified by the PHY clause then a <i>phyCcaDuration</i> of 8 symbol periods is recommended.
<i>phyCcaMode</i>	Enumeration	MODE_1, MODE_2, MODE_3A, MODE_3B, MODE_4, MODE_5, MODE_6	The CCA mode, as defined in 11.2.8.

Table 12-2—Generic PHY PIB attributes (*continued*)

Attribute	Type	Range	Description
<i>phyCurrentChannelInfo</i>	Channel Information structure as defined in 11.1.3.1	PHY dependent as defined in 11.1.3.1	The RF channel to use for all following transmissions and receptions.
<i>phyCcaEdThreshold</i>	Implementation dependent	Implementation dependent	Threshold value for energy above threshold used in CCA. Typically specified in units of power, e.g., dBm, relative to a given frequency bandwidth, for example at most 10 dB greater than the specified receiver sensitivity for that PHY.
<i>phyMaxPacketSize</i>	Integer	16–4095	The maximum PSDU size (in octets) the PHY shall be able to receive. This is 2047 for the following PHYs: SUN, TVWS, RCC, LECIM FSK, and MSK with a 2000 kb/s data rate. For LECIM DSSS PHY, refer to <i>phyLecimDsssPsduSize</i> . For the HRP UWB PHY, refer to <i>phyHrpUwbPsduSize</i> . 127 for all other PHYs.
<i>phyMaxTxPower</i>	Signed integer†	—	Upper-bound level of the transmit power of the device that is capable to use.
<i>phyPeersTxPower</i>	List of parameters as defined in Table 12-3	—	List of exceptions to the <i>phyUnicastTxPower</i> while transmitting to specific peer devices.
<i>phyRanging</i>	Boolean†	TRUE, FALSE	TRUE if ranging is supported, FALSE otherwise.
<i>phyRxRmarkerOffset</i>	Integer	0x00000000–0xffffffff	A count of the propagation time from the receive antenna to the ranging counter. The time units for this are as specified in 10.29.1.4.
<i>phyTxPower</i>	Signed integer	—	Currently configured upper-bound level of the transmit power of the device that shall be equal or less than <i>phyMaxTxPower</i> in dBm.
<i>phyTxRmarkerOffset</i>	Integer	0x00000000–0xffffffff	A count of the propagation time from the ranging counter to the transmit antenna. The time units for this are as specified in 10.29.1.4.
<i>phyUnicastTxPower</i>	Signed integer	—	Transmit power in dBm while sending a unicast. This value is managed by an upper layer but shall be lower or equal to <i>phyTxPower</i> .

NOTE—Optimal values for CCA parameters will depend upon variables outside the scope of this standard; In some regions, regulations define specific constraints that vary region to region.

Table 12-3—Elements of *phyPeersTxPower*

Attribute	Type	Range	Description
deviceAddrMode	Enumeration	SHORT, EXTENDED	The addressing mode of the peer device.
deviceAddress	Short address or extended address	As specified by the deviceAddrMode parameter	Address of the peer device.
TxPower	Signed integer	—	The value to be placed in the <i>phyTxPower</i> PIB Attribute when the device is transmitting to the device with the address deviceAddress.

12.3.3 Generic LECIM PHY related PIB attributes

Generic PIB attributes related to the LECIM PHY are presented in Table 12-4.

Table 12-4—LECIM Related PIB attributes

Attribute	Type	Range	Description
<i>phyLecimChannelSpacing</i>	Enumeration	12.5, 100, 200, LECIMBASE, 2LECIMBASE, 4LECIMBASE, 8LECIMBASE	The channel spacing that is used with <i>phyLecimCurrentBand</i> and <i>phyCurrentChannelInfo</i> to specify the frequency channel being used. 12.5 corresponds to 12.5 kHz, 100 corresponds to 100 kHz, 200 corresponds to 200 kHz, LECIMBASE corresponds to <i>lecimBaseMultiplier</i> kHz, 2LECIMBASE corresponds to $2 \times \text{lecimBaseMultiplier}$ kHz, 4LECIMBASE corresponds to $4 \times \text{lecimBaseMultiplier}$ kHz, and 8LECIMBASE corresponds to $8 \times \text{lecimBaseMultiplier}$ kHz.
<i>phyLecimCurrentBand</i>	Enumeration	169, 262, 433, 470, 780, 863, 915, 917, 920, 921, 922, 2450	The operating frequency band currently selected.
<i>phyLecimCurrentPhyType</i>	Enumeration	DSSS, FSK	Specifies the LECIM PHY type in use.
<i>phyPsduFragEnabled</i>	Boolean	TRUE, FALSE	When TRUE, PSDU fragmentation is enabled. See 24.4. When FALSE, PSDU fragmentation is disabled.
<i>phyPsduFragFrame-Counter</i>	Integer	0x000000–0x3fffff	The outgoing PSDU counter to use when <i>phyPsduFragSecure</i> is TRUE. The counter is not used when <i>phyPsduFragSecure</i> is FALSE.
<i>phyPsduFragPadValue</i>	Integer	0–255	The value used to pad out the last fragment when MPDU fragmentation is enabled.

Table 12-4—LECIM Related PIB attributes (continued)

Attribute	Type	Range	Description
<i>phyPsduFragSecure</i>	Boolean	TRUE, FALSE	When set to TRUE, a MIC shall be used as the FICS, as described in 10.15.2.1. When set to FALSE, the FICS shall be calculated as in 7.2.11.
<i>phyPsduFragSize</i>	Integer	PHY dependent	The number of octets in each fragment.
<i>phyPsduFrakProgress-Timeout</i>	Integer	—	The duration, in modulated symbols, at which to generate a Frak frame when Frak policy 1 is in use.

12.3.4 LECIM DSSS related PIB attributes

PIB attributes related to the LECIM DSSS PHY are presented in Table 12-5.

Table 12-5—LECIM DSSS related PIB attributes

Attribute	Type	Range	Description
<i>phyLecimDsssFecTail-BitingEnabled</i>	Boolean	TRUE, FALSE	A value of TRUE indicates that tail biting is enabled. A value of FALSE indicates that it is disabled.
<i>phyLecimDsssP pduModulationRate</i>	Enumeration	100, 200, 400, 600, 800, 1000, 2000	The modulation rate measured in modulation kilo symbols per second.
<i>phyLecimDsssP pduTxAt</i>	Integer	0-[2 ³² - 1]	The time, in modulation symbols, relative to the start of the beacon.
<i>phyLecimDsssPreamble-Size</i>	Enumeration	0, 16, 32	The length of the preamble, as illustrated in Table 23-1.
<i>phyLecimDsssPsduOvsf-CodeIndex</i>	Integer	0, 1, ..., N - 1	Specifies the desired code from the available set of codes. The value of N is given by <i>phyLecimDsssPsduSpreadingFactor</i> .
<i>phyLecimDsssPsduOvsf-SpreadingFactor</i>	Integer	1-256	The length of the generated code in power of 2. A value of one indicates that OVSF is not enabled.
<i>phyLecimDsssPsduSize</i>	Enumeration	16, 24, 32	The size, in octets, of the PSDU.
<i>phyLecimDsssPsduS-spreadingFactor</i>	Integer	4-15	2 ^x chips per symbol where x is in the range 4 to 15, inclusive.
<i>phyLecimDsssSfdPresent</i>	Boolean	TRUE, FALSE	A value of TRUE indicates that the SFD is present. A value of FALSE indicates that the SFD is not present.

12.3.5 LECIM FSK related PIB attributes

PIB attributes related to the LECIM FSK PHY are presented in Table 12-6.

Table 12-6—LECIM FSK related PIB attributes

Attribute	Type	Range	Description
<i>phyLecimFskFecEnabled</i>	Boolean	TRUE, FALSE	A value of TRUE indicates that FEC is turned on. A value of FALSE indicates that FEC is turned off.
<i>phyLecimFskInterleavingEnabled</i>	Boolean	TRUE, FALSE	A value of TRUE indicates that interleaving is turned on. A value of FALSE indicates that interleaving is turned off.
<i>phyLecimFskPreambleLength</i>	Integer	0–64	The number of times the preamble contains the pattern defined in 24.3.2.2.
<i>phyLecimFskPsduPositionMod</i>	Boolean	TRUE, FALSE	Indicates whether position-based modulation is enabled. A value of TRUE indicates that position-based modulation is enabled. A value of FALSE indicates that it is not enabled.
<i>phyLecimFskSfdSpreading</i>	Boolean	TRUE, FALSE	A value of TRUE indicates that SFD spreading is enabled. A value of FALSE indicates that SFD spreading is disabled.
<i>phyLecimFskSplit</i>	Boolean	TRUE, FALSE	Indicates use of split mode as defined in 24.2.
<i>phyLecimFskSplitBurstDistribution</i>	Enumeration	FIXED, CUSTOM	The radio-burst distribution method to use as defined in 24.4.8.
<i>phyLecimFskSplitChannelMultiplier</i>	Integer	1–255	Spacing between two channels actively used for transmission in split mode.
<i>phyLecimFskSplitFec</i>	Enumeration	IR2-CC, IR3-CC, IR4-LDPC	FEC scheme to use as described in 24.4.5.3.
<i>phyLecimFskSpreading</i>	Boolean	TRUE, FALSE	A value of TRUE indicates that spreading is enabled. A value of FALSE indicates that spreading is disabled.
<i>phyLecimFskSymbolRate</i>	Float	As defined in Table 11-3	The currently selected symbol rate in ksymbols per second. The valid symbol rates per band are given in Table 11-3.

12.3.6 LRP UWB related PIB attributes

PIB attributes related to the LRP UWB PHY are presented in Table 12-7.

Table 12-7—LRP UWB related PIB attributes

Attribute	Type	Range	Description
<i>phyLrpUwbFixedDelayFactor</i>	Integer	1–32 767	Defines the reply delay factor that multiplies the <i>phyLrpUwbFixedReplyTime</i> to be used in multi-node ranging.
<i>phyLrpUwbFixedReplyTime</i>	Enumeration	FRT4, FRT8, FRT16, FRT32	For LRP-ERDEV this attribute selects the fixed reply time as specified in Table 19-15.
<i>phyLrpUwbFixedReplyTimeSupported</i>	Boolean	TRUE, FALSE	A value of TRUE indicates the RDEV can support a fixed reply time. A value of FALSE indicates that the RDEV does not support a fixed reply time.
<i>phyLrpUwbPrp</i>	Integer	0–7	Selects the pulse repetition period (PRP) to be used, as specified in 19.2.6. The value corresponds to the factor kPRP defined in Table 19-6.
<i>phyLrpUwbSfdSelector</i>	Integer	0–9	This attribute selects the SFD pattern to be used by the transmitter and receiver, as specified in 19.3.3.2 and Table 19-7.
<i>phyLrpUwbSignaling</i>	Integer	0–15	For the LRP UWB PHY, when attribute is non-zero, it configures the PHY to receive with the signaling scheme defined in Table 19-1.

12.3.7 HRP UWB related PIB attributes

PIB attributes related to the HRP UWB PHY are presented in Table 12-8.

Table 12-8—HRP UWB related PIB attributes

Attribute	Type	Range	Description
<i>phyHrpUwbCcConstraintLength</i>	Enumeration	CL3, CL7	For HRP-ERDEV in the HPRF mode, this attribute specifies the constraint length of the convolutional code in use by the transmitter and receiver applying to the PHR and PSDU, that is selecting between the K = 3 and K = 7 convolution encoding specified in 16.3.3. When not in HPRF mode, the constraint length shall be three and this attribute shall be ignored.
<i>phyHrpUwbCurrentPulseShape</i>	Enumeration	MANDATORY, COU, CS, LCP	Indicates the current pulse shape setting of the HRP UWB PHY. The mandatory pulse is described in 16.4.4. Optional pulse shapes include CoU, as defined in 16.5.2; CS, as defined in 16.5.3; and LCP, as defined in 16.5.4.
<i>phyHrpUwbDataRatesSupported</i>	List of integers†	—	A list of the data rates available in the operating channel as defined in Table 16-12.

Table 12-8—HRP UWB related PIB attributes (*continued*)

Attribute	Type	Range	Description
<i>phyHrpUwbInsertedPreambleInterval</i>	Enumeration	0, 4	The time interval between two neighboring inserted preamble symbols in the data portion, as defined in 16.6, for HRP UWB PHYs operating with CCA mode 6. The resolution is a data symbol period at a data rate of 850 kb/s for all channels. Set to four for HRP UWB PHY in CCA mode 6; otherwise, set to zero.
<i>phyHrpUwbLcpDelay2</i>	Integer	0x00–0xff	The range is from 0 to 4 ns with a resolution is 15.625 ps. For example, a value of 0x00 represents 0 while 0x02 represents 31.25 ps, as defined in 16.5.4.
<i>phyHrpUwbLcpDelay3</i>	Integer	0x00–0xff	The range is from 0 to 4 ns with a resolution is 15.625 ps. For example, a value of 0x00 represents 0 while 0x02 represents 31.25 ps, as defined in 16.5.4.
<i>phyHrpUwbLcpDelay4</i>	Integer	0x00–0xff	The range is from 0 to 4 ns with a resolution is 15.625 ps. For example, a value of 0x00 represents 0 while 0x02 represents 31.25 ps, as defined in 16.5.4.
<i>phyHrpUwbLcpWeight1</i>	Signed integer	0x00–0xff	The weights are represented in twos-complement form. A value of 0x80 represents -1 while a value of 0x7f represents 1.
<i>phyHrpUwbLcpWeight2</i>	Signed integer	0x00–0xff	The weights are represented in twos-complement form. A value of 0x80 represents -1 while a value of 0x7f represents 1.
<i>phyHrpUwbLcpWeight3</i>	Signed integer	0x00–0xff	The weights are represented in twos-complement form. A value of 0x80 represents -1 while a value of 0x7f represents 1.
<i>phyHrpUwbLcpWeight4</i>	Signed integer	0x00–0xff	The weights are represented in twos-complement form. A value of 0x80 represents -1 while a value of 0x7f represents 1.
<i>phyHrpUwbPhrA0</i>	Integer	0, 1	For HRP-ERDEVs in HPRF mode, this attribute specifies the value of the A0 field of the transmitted PHR, unless it is being used to extend the PHY payload length field as described in 16.2.7.3.
<i>phyHrpUwbPhrA1</i>	Integer	0, 1	For HRP-ERDEVs in HPRF mode, this attribute specifies the value of the A1 field of the transmitted PHR, unless it is being used to extend the PHY payload length field as described in 16.2.7.3.

Table 12-8—HRP UWB related PIB attributes (*continued*)

Attribute	Type	Range	Description
<i>phyHrpUwbPhrDataRate</i>	Enumeration	DRMDR, DRBM_LP, DRBM_HP, DRHM_LR, DRHM_HR	When equal to DRMDR, the bit rate is specified by the DataRate parameter of the MCPS-DATA.request primitive, otherwise the transmit and receive bit rates for PHR and Data are selected by this attribute as specified in Table 16-14 and Table 16-22.
<i>phyHrpUwbPsduSize</i>	Integer	0–2	For HRP-ERDEVs in HPRF mode, this attribute specifies the use of the A0 and A1 fields of the PHR to extend the maximum PSDU length, as specified in 16.2.7.3 and Table 16-16.
<i>phyHrpUwbPsr</i>	Integer	0, 16, 24, 32, 48, 64, 96, 128, 256	When non-zero, this attribute specifies the length, in symbols, of the SYNC field to be sent by the transmitter and expected by the receiver in an HRP-ERDEV, see 16.2.6.2.
<i>phyHrpUwbScanBinsPerChannel</i>	Integer	0–255	Number of frequency intervals used to scan each HRP UWB channel (scan resolution).
<i>phyHrpUwbSfdSelector</i>	Integer	0–4	This attribute selects the SFD pattern to be used by the transmitter and receiver, as specified in 16.2.6.3 and Table 16-11.
<i>phyHrpUwbStsPC2RxGap0</i>	Integer	0–127	When <i>phyHrpUwbStsRxPacketConfig</i> is two, this attribute specifies the duration of an additional gap in units of 4 chips (~8 ns), between the PSDU and the STS, to be expected by the receiver, as per Table 16-15.
<i>phyHrpUwbStsPC2RxGap1</i>	Integer	0–127	When <i>phyHrpUwbStsRxPacketConfig</i> is two, this attribute specifies the duration of an additional gap in units of 4 chips (~8 ns), between the PSDU and the STS, to be expected by the receiver, as per Table 16-15.
<i>phyHrpUwbStsPC2RxGap2</i>	Integer	0–127	When <i>phyHrpUwbStsRxPacketConfig</i> is two, this attribute specifies the duration of an additional gap in units of 4 chips (~8 ns), between the PSDU and the STS, to be expected by the receiver, as per Table 16-15.
<i>phyHrpUwbStsPC2RxGap3</i>	Integer	0–127	When <i>phyHrpUwbStsRxPacketConfig</i> is two, this attribute specifies the duration of an additional gap in units of 4 chips (~8 ns), between the PSDU and the STS, to be expected by the receiver, as per Table 16-15.

Table 12-8—HRP UWB related PIB attributes (*continued*)

Attribute	Type	Range	Description
<i>phyHrpUwbStsPC2TxGap</i>	Integer	0–127	When <i>phyHrpUwbStsRxPacketConfig</i> is two, this attribute specifies the duration of an additional gap in units of 4 chips (~8 ns), between the PSDU and the STS, to be inserted by the transmitter, as per 16.2.7.3.
<i>phyHrpUwbStsRxPacketConfig</i>	Integer†	0–3	This attribute indicates the presence and position of the STS field in the PPDU expected by the receiver, as per Table 16-1.
<i>phyHrpUwbStsRxSegLen</i>	Integer†	0–3	This attribute indicates the length of active STS segment(s) in the PPDU expected by the receiver, as specified in Table 16-18.
<i>phyHrpUwbStsRxSegNum</i>	Integer†	0–3	This attribute indicates the number of STS segments in the PPDU expected by the receiver, as specified in Table 16-18.
<i>phyHrpUwbStsSeed</i>	16 octets	—	This attribute specifies the STS seed used in the DRBG for generating the STS. When the DRBG is running, write access to this attribute shall be delayed until after packet transmission/reception.
<i>phyHrpUwbStsTxPacketConfig</i>	Integer†	0–3	This attribute indicates the presence and position of the STS field in the transmitted PPDU as per Table 16-1.
<i>phyHrpUwbStsTxSegLen</i>	Integer†	0–3	This attribute indicates the length of active STS segment(s) in the transmitted PPDU, as specified in Table 16-18.
<i>phyHrpUwbStsTxSegNum</i>	Integer†	0–3	This attribute indicates the number of STS segments in the transmitted PPDU, as specified in Table 16-18.
<i>phyHrpUwbStsVCounter</i>	4 octets	—	This attribute provides read and write access to the 32-bit counter that supplies the least significant 32 bits of the 128-bit value V used in the DRBG for generating the STS. See 16.2.9. During packet transmission or reception, this attribute shall not be writable, and a read shall provide the initial state of the attribute at the beginning of packet transmission/reception.
<i>phyHrpUwbStsVUpper96</i>	12 octets	—	This attribute supplies the most significant 96 bits of the 128-bit value V used in the DRBG for generating the STS. See 16.2.9. This attribute shall not be modified during packet transmission or reception.

12.3.8 TVWS related PIB attributes

PIB attributes related to the TVWS PHY are presented in Table 12-9.

Table 12-9—TVWS related PIB attributes

Attribute	Type	Range	Description
<i>phyTvwsChannelAggregation</i>	Boolean	TRUE, FALSE	A value of TRUE indicates that channel aggregation is enabled. A value of FALSE indicates that channel aggregation is disabled. This attribute is only valid for the TVWS-NB-OFDM PHY.
<i>phyTvwsFskFecScheme</i>	Integer	0–2	A value of zero indicates that the first FEC scheme as defined in 25.2.3 is employed. A value of one indicates that the second FEC scheme as defined in 25.2.3 is employed. A value of two indicates that the third FEC scheme as defined in 25.2.3 is employed.
<i>phyTvwsFskSfdLength</i>	Integer	16 or 24	Length of the TVWS SFD field in bits.
<i>phyTvwsFskSpreadingEnabled</i>	Boolean	TRUE, FALSE	A value of TRUE indicates that spreading is turned on. A value of FALSE indicates that spreading is turned off.
<i>phyTvwsFskWhiteningEnabled</i>	Boolean	TRUE, FALSE	A value of TRUE indicates that whitening is turned on. A value of FALSE indicates that whitening is turned off.

12.3.9 RS-GFSK related PIB attributes

PIB attributes related to the RS-GFSK PHY are presented in Table 12-10.

Table 12-10—RS-GFSK related PIB attributes

Attribute	Type	Range	Description
<i>phyRsGfskPreambleLength</i>	Integer	2–15	This attribute is the number of repetitions of 1-octet patterns, as described in 32.1.2, in the preamble of an RS-GFSK PHY.
<i>phyRsGfskPrecode</i>	Boolean	TRUE, FALSE	If TRUE, differential encoding, as described in 32.2.3, is employed for the RS-GFSK PHY. If FALSE, it is not.
<i>phyRsGfskSfd</i>	Integer	0, 1	This attribute determines which group of SFDs is used, as described in Table 32-1.
<i>phyRsGfskShortPhrEnabled</i>	Boolean	TRUE, FALSE	This attribute indicates whether the device is using Short PHR in its transmission as described in 32.1.5. If TRUE, the device is using Short PHR. If FALSE, it is using a Long PHR.

12.3.10 FSK related PIB attributes

PIB attributes related to the different FSK PHYs are presented in Table 12-11.

Table 12-11—FSK related PIB attributes

Attribute	Type	Range	Description
<i>phyFskFecEnabled</i>	Boolean	TRUE, FALSE	A value of TRUE indicates that FEC is turned on. A value of FALSE indicates that FEC is turned off. This attribute is only valid for the SUN FSK, TVWS FSK, and RS-GFSK PHY.
<i>phyFskFecInterleavingRsc</i>	Boolean	TRUE, FALSE	A value of TRUE indicates that interleaving is enabled for RSC. A value of FALSE indicates that interleaving is disabled for RSC. This attribute is only valid for the SUN FSK and TVWS FSK PHY.
<i>phyFskFecScheme</i>	Integer	0, 1	A value of zero indicates that a non-recursive and non-systematic code (NRNSC) is employed. A value of one indicates that a recursive and systematic code (RSC) is employed. See 20.3.5 for more information on FEC. This attribute is only valid for the SUN FSK PHY and CMB FSK PHY.
<i>phyFskPreambleLength</i>	Integer	4–64	The number of repetitions of the preamble pattern, as described in 20.2.2.2 and 25.1.2.2, in the preamble. This attribute is only valid for the SUN FSK and TVWS FSK PHY.
<i>phyFskSpreadingFactor</i>	Enumeration	1, 2, 4, 8, 16	The spreading factor to be used when <i>phyLecimFskSpreading</i> or <i>phyTvwsFskSpreadingEnabled</i> is TRUE. This attribute is only valid for the LECIM FSK and TVWS FSK PHY.
<i>phyFskSpreadingPattern</i>	Enumeration	ALTERNATING_1/0, NON_ALTERNATING	Specifies the type of pattern used for spreading when spreading is enabled. This attribute is only valid for the LECIM FSK and TVWS FSK PHY.

12.3.11 SUN FSK PHY related PIB attributes

PIB attributes related to the SUN FSK PHY are presented in Table 12-12 and Table 12-13 presents the ModeSwitchDescriptor entries.

Table 12-12—SUN FSK related PIB attributes

Attribute	Type	Range	Description
<i>phySunFskScramblePsdu</i>	Boolean	TRUE, FALSE	A value of FALSE indicates that data whitening of the PSDU is disabled. A value of TRUE indicates that data whitening of the PSDU is enabled.
<i>phySunFskSfd</i>	Integer	0, 1	Determines which group of SFDs is used, as described in Table 20-2.

Table 12-12—SUN FSK related PIB attributes (*continued*)

Attribute	Type	Range	Description
<i>phySunModeSwitchEnable</i>	Boolean	TRUE, FALSE	A value of TRUE indicated that mode switch as described in 20.5 is enabled.
<i>phySunModeSwitchParameterEntries</i>	Array	As defined in Table 12-13	An array of up to four rows, where each row consists of a set of ModeSwitchDescriptor entries.

Table 12-13—Elements of ModeSwitchDescriptor

Name	Type	Valid range	Description
SecondaryFskPreambleLength	Integer	0–16	The number of 1-octet patterns, as described in 20.2.2.2, in the secondary preamble if the new mode is SUN FSK. This parameter does not apply if the new mode is SUN OFDM or SUN O-QPSK.
SecondaryFskSfd	Boolean	TRUE, FALSE	If the new mode is SUN FSK, a value of TRUE indicates that a secondary SFD is transmitted. A value of FALSE indicates that a secondary SFD is not transmitted. This parameter does not apply if the new mode is SUN OFDM or SUN O-QPSK.
SettlingDelay	Integer	0–510	The settling delay, in microseconds, between the end of the final symbol of the PPDU initiating the mode switch and the start of the PPDU transmitted using the new PHY mode.

12.3.12 Other PHY related PIB attributes

PIB attributes related to the different PHYs are presented in Table 12-14.

Table 12-14—Other PHY related PIB attributes

Attribute	Type	Range	Description
<i>phyCurrentCode</i>	Integer	0–32	This value is zero for PHYs other than HRP UWB PHY or CSS PHY. For HRP UWB PHYs, this represents the current preamble code index in use by the transmitter and receiver, as defined in Table 16-7, Table 16-8, and Table 16-9. For the CSS PHY, the value indicates the subchirp, as defined in 15.3.
<i>phyLmrCodingRate</i>	Float	1/2, 2/3, 3/4, 7/8, 1	Controls which puncturing pattern is used for the PSDU, as described in 28.3. If the attribute value is one, then FEC shall not be applied.
<i>phyOfdmInterleaving</i>	Integer	0, 1	A value of zero indicates an interleaving depth of one symbol. A value of one indicates an interleaving depth of the number of symbols equal to the frequency domain spreading factor. This attribute is only valid for the SUN OFDM PHY.

13. O-QPSK PHY

13.1 PPDU format

13.1.1 General

The PPDU shall be formatted as illustrated in Figure 13-1.

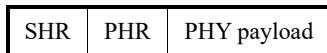


Figure 13-1—Format of the PPDU

13.1.2 SHR field format

13.1.2.1 General

The SHR field shall be formatted as illustrated in Figure 13-2.

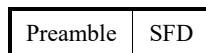


Figure 13-2—Format of the SHR

13.1.2.2 Preamble field

The length of the Preamble field for the O-QPSK PHYs shall be 8 symbols (i.e., 4 octets), and the bits in the Preamble field shall be binary zeros.

13.1.2.3 SFD field

The SFD is a field indicating the end of the SHR and the start of the packet data. The SFD shall be formatted as illustrated in Figure 13-3.

Bits: 0	1	2	3	4	5	6	7
1	1	1	0	0	1	0	1

Figure 13-3—Format of the SFD field

13.1.3 PHR field format

13.1.3.1 General

The PHR field shall be formatted as illustrated in Figure 13-4.

Bits: 0–6	7
Frame Length	Reserved

Figure 13-4—Format of the PHR

13.1.3.2 Frame Length field

The Frame Length field specifies the total number of octets contained in the PSDU (i.e., PHY payload).

13.1.3.3 PHY Payload field

The PHY Payload field carries the PSDU.

13.2 Modulation and spreading

13.2.1 General

The O-QPSK PHY employs a 16-ary quasi-orthogonal modulation technique. During each data symbol period, four information bits are used to select 1 of 16 nearly orthogonal pseudo-random noise (PN) sequences to be transmitted. The PN sequences for successive data symbols are concatenated, and the aggregate chip sequence is modulated onto the carrier using offset quadrature phase-shift keying (O-QPSK).

13.2.2 Data rate

The data rate of the O-QPSK PHY shall be 250 kb/s when operating in the 2450 MHz, 915 MHz, 780 MHz or 2380 MHz bands and shall be 100 kb/s when operating in the 868 MHz band.

Support for the 2450 MHz O-QPSK PHY is mandatory when operating in the 2450 MHz band.

Support for the 2380 MHz O-QPSK PHY is mandatory when operating in the 2380 MHz band.

The O-QPSK PHY is not mandatory in the 868 MHz or 915 MHz band. If the O-QPSK PHY is used in the 868 MHz or 915 MHz band, then the same device shall be capable of signaling using the BPSK PHY as well.

13.2.3 Reference modulator diagram

The functional block diagram in Figure 13-5 is provided as a reference for specifying the O-QPSK PHY modulation and spreading functions.

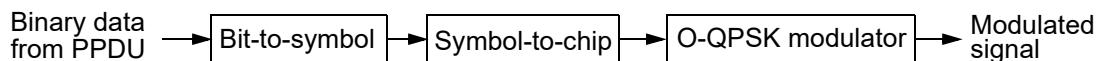


Figure 13-5—Modulation and spreading functions for the O-QPSK PHYs

13.2.4 Bit-to-symbol mapping

All binary data contained in the PPDU shall be encoded using the modulation and spreading functions shown in Figure 13-5. This subclause describes how binary information is mapped into data symbols.

The 4 LSBs (b0, b1, b2, b3) of each octet shall map into one data symbol, and the 4 MSBs (b4, b5, b6, b7) of each octet shall map into the next data symbol. Each octet of the PPDU is processed through the modulation and spreading functions, as illustrated in Figure 13-5, sequentially, beginning with the Preamble field and ending with the last octet of the PSDU. Within each octet, the least significant symbol (b0, b1, b2, b3) is processed first and the most significant symbol (b4, b5, b6, b7) is processed second.

13.2.5 Symbol-to-chip mapping

In the 2450 MHz and 2380 MHz bands, each data symbol shall be mapped into a 32-chip PN sequence as specified in Table 13-1. The PN sequences are related to each other through cyclic shifts and/or conjugation (i.e., inversion of odd-indexed chip values).

Table 13-1—Symbol-to-chip mapping for the 2450 MHz and 2380 MHz bands

Data symbol	Chip values ($c_0 c_1 \dots c_{30} c_{31}$)
0	1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0
1	1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0
2	0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0
3	0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0
4	0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 0 0 1 1 1 0 0 0 0 1 1 0 1
5	0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0
6	1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 1 1 0
7	1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0
8	1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1
9	1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 1 1 1 0 1 1 1 1
10	0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 1 1 1
11	0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0
12	0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0
13	0 1 1 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1
14	1 0 0 1 0 1 1 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0
15	1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0

In the 915 MHz, 868 MHz, and 780 MHz bands, each data symbol shall be mapped into a 16-chip PN sequence as specified in Table 13-2.

Table 13-2—Symbol-to-chip mapping for the 915 MHz, 868 MHz, and 780 MHz bands

Data symbol	Chip values ($c_0 c_1 \dots c_{14} c_{15}$)
0	0 0 1 1 1 1 1 0 0 0 1 0 0 1 0 1
1	0 1 0 0 1 1 1 1 1 0 0 0 1 0 0 1
2	0 1 0 1 0 0 1 1 1 1 1 0 0 0 1 0
3	1 0 0 1 0 1 0 0 1 1 1 1 1 0 0 0
4	0 0 1 0 0 1 0 1 0 0 1 1 1 1 1 0
5	1 0 0 0 1 0 0 1 0 1 0 0 1 1 1 1

Table 13-2—Symbol-to-chip mapping for the 915 MHz, 868 MHz, and 780 MHz bands (continued)

Data symbol	Chip values ($c_0 c_1 \dots c_{14} c_{15}$)
6	1 1 1 0 0 0 1 0 0 1 0 1 0 0 1 1
7	1 1 1 1 1 0 0 0 1 0 0 1 0 1 0 0
8	0 1 1 0 1 0 1 1 0 1 1 1 0 0 0 0
9	0 0 0 1 1 0 1 0 1 1 0 1 1 1 0 0
10	0 0 0 0 0 1 1 0 1 0 1 1 0 1 1 1
11	1 1 0 0 0 0 0 1 1 0 1 0 1 1 0 1
12	0 1 1 1 0 0 0 0 0 1 1 0 1 0 1 1
13	1 1 0 1 1 1 0 0 0 0 0 0 1 1 0 1 0
14	1 0 1 1 0 1 1 1 0 0 0 0 0 1 1 0
15	1 0 1 0 1 1 0 1 1 1 0 0 0 0 0 1

13.2.6 O-QPSK modulation

The chip sequences representing each data symbol are modulated onto the carrier using O-QPSK with half-sine pulse shaping. Even-indexed chips are modulated onto the in-phase (I) carrier, and odd-indexed chips are modulated onto the quadrature-phase (Q) carrier. In the 2450 MHz and 2380 MHz bands, each data symbol is represented by a 32-chip sequence, and so the chip rate is 32 times the symbol rate. In the 915 MHz, 868 MHz, and 780 MHz bands, each data symbol is represented by a 16-chip sequence, and so the chip rate is 16 times the symbol rate. To form the offset between I-phase and Q-phase chip modulation, the Q-phase chips shall be delayed by T_c with respect to the I-phase chips, as illustrated in Figure 13-6, where T_c is the inverse of the chip rate.

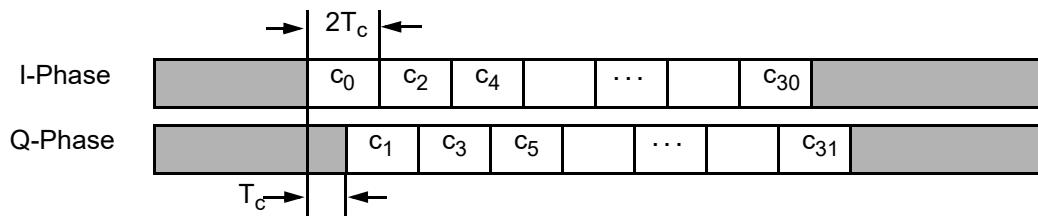


Figure 13-6—O-QPSK chip offsets

13.2.7 Pulse shape

In the 2450 MHz, 915 MHz, 868 MHz, and 2380 MHz bands, the half-sine pulse shape is used to represent each baseband chip and is as follows:

$$p(t) = \begin{cases} \sin\left(\pi \frac{t}{2T_c}\right), & 0 \leq t \leq 2T_c \\ 0, & \text{otherwise} \end{cases}$$

Figure 13-7 shows a sample baseband chip sequence (the zero sequence) with half-sine pulse shaping.

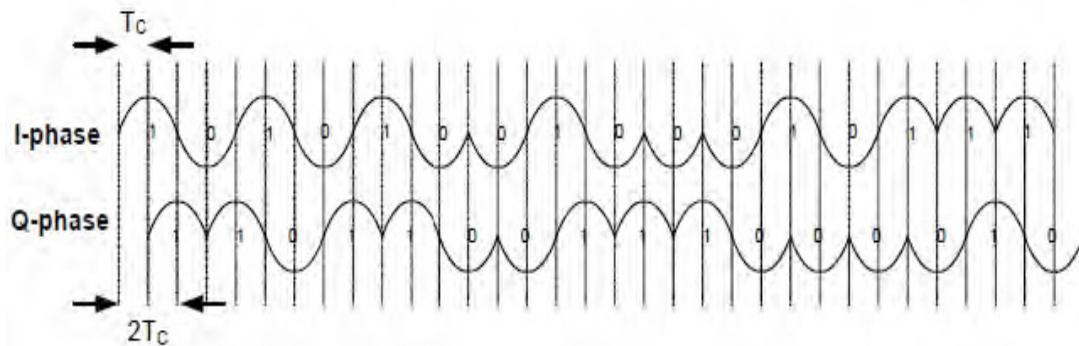


Figure 13-7—Sample baseband chip sequences with pulse shaping

In the 780 MHz band, a raised cosine pulse shape with roll-off factor of $r = 0.8$ is used to represent each baseband chip and is described as follows:

$$p(t) = \begin{cases} \frac{\sin(\pi t/T_c)}{\pi t/T_c} \times \frac{\cos(r\pi t/T_c)}{1 - 4r^2 t^2/T_c^2}, & t \neq 0 \\ 1, & t = 0 \end{cases}$$

Given the discrete-time sequence of consecutive complex-valued chip samples, c_k , the continuous-time pulse shaped complex baseband signal is as follows:

$$y(t) = \sum_{k=-\infty}^{\infty} c_{2k} p(t - 2kT_c) + j c_{2k+1} p(t - 2kT_c - T_c)$$

13.2.8 Chip transmission order

During each symbol period, the least significant chip, c_0 , is transmitted first and the most significant chip, either c_{31} , for the 2450 MHz and 2380 MHz bands, or c_{15} , for the 915 MHz, 868 MHz, and 780 MHz bands, is transmitted last.

13.3 O-QPSK PHY RF requirements

13.3.1 Operating frequency range

The O-OPSK PHY operates in the following bands:

- 779–787 MHz
 - 868.0–868.6 MHz
 - 902–928 MHz
 - 2360–2400 MHz
 - 2400.0–2483.5 MHz

13.3.2 Transmit power spectral density (PSD) mask

When operating in the 868 MHz band, the signal shall be filtered before transmission to regulate the transmit PSD. The filter shall approximate an ideal raised cosine filter with a roll-off factor $r = 0.2$, as follows:

$$p(t) = \begin{cases} \frac{\sin \pi t/T_c}{\pi t/T_c} \frac{\cos r\pi t/T_c}{1 - 4r^2 t^2/T_c^2}, & t \neq 0 \\ 1, & t = 0 \end{cases}$$

When operating in the 915 MHz or 780 MHz band, the transmitted spectral products shall be less than the limits specified in Table 13-3. For both relative and absolute limits, average spectral power shall be measured using a 100 kHz resolution bandwidth. For the relative limit, the reference level shall be the highest average spectral power measured within ± 600 kHz of the carrier frequency f_c .

Table 13-3—O-QPSK PHY transmit PSD limits for the 915 MHz and 780 MHz bands

Frequency	Relative limit	Absolute limit
$ f - f_c > 1.2$ MHz	-20 dB	-20 dBm

When operating in the 2380 MHz or 2450 MHz band, the transmitted spectral products shall be less than the limits specified in Table 13-4. For both relative and absolute limits, average spectral power shall be measured using a 100 kHz resolution bandwidth. For the relative limit, the reference level shall be the highest average spectral power measured within ± 1 MHz of the carrier frequency.

Table 13-4—O-QPSK transmit PSD limits for the 2380 MHz and 2450 MHz bands

Frequency	Relative limit	Absolute limit
$ f - f_c > 3.5$ MHz	-20 dB	-30 dBm

13.3.3 Symbol rate

The O-QPSK PHY symbol rate shall be 25 ksymbol/s when operating in the 868 MHz band and 62.5 ksymbol/s when operating in the 780 MHz, 915 MHz, 2380 MHz, or 2450 MHz band with an accuracy of $\pm 40 \times 10^{-6}$.

13.3.4 Receiver sensitivity

Under the conditions specified in 11.1.8, a compliant device shall be capable of achieving a receiver sensitivity of -85 dBm or better.

13.3.5 Receiver interference rejection

This subclause applies only to the 780 MHz, 915 MHz, 2380 MHz, and 2450 MHz bands because there is only one channel available in the 868 MHz band.

The minimum receiver interference rejection levels are given in Table 13-5. The adjacent channel is one on either side of the desired channel that is closest in frequency to the desired channel, and the alternate channel

is one more removed from the adjacent channel. For example, when channel 5 is the desired channel, channel 4 and channel 6 are the adjacent channels, and channel 3 and channel 7 are the alternate channels.

Table 13-5—Minimum receiver interference rejection requirements for the 780 MHz, 915 MHz, 2380 MHz, and 2450 MHz bands

Adjacent channel rejection	Alternate channel rejection
0 dB	30 dB

The adjacent channel rejection shall be measured as follows: the desired signal shall be a compliant O-QPSK PHY signal, as defined in 13.2, of pseudo-random data. The desired signal is input to the receiver at a level 3 dB greater than the maximum allowed receiver sensitivity given in 13.3.4.

In either the adjacent or the alternate channel, a compliant O-QPSK PHY signal, as defined by 13.2, is input at the level specified in Table 13-5 relative to the desired signal. The test shall be performed for only one interfering signal at a time. The receiver shall meet the error rate criteria defined in 11.1.8 under these conditions.

13.3.6 TX-to-RX turnaround time

The O-QPSK PHY shall have a TX-to-RX turnaround time as defined in 11.2.2.

13.3.7 RX-to-TX turnaround time

The O-QPSK PHY shall have an RX-to-TX turnaround time as defined in 11.2.3.

13.3.8 EVM

The O-QPSK PHY shall have EVM values of less than 35% when measured for 1000 chips using the measurement process defined in 11.2.4.

13.3.9 Transmit center frequency tolerance

The O-QPSK PHY transmit center frequency tolerance shall be $\pm 40 \times 10^{-6}$ maximum.

13.3.10 Transmit power

The O-QPSK PHY shall be capable of transmitting at a power level of at least -3 dBm.

13.3.11 Receiver maximum input level of desired signal

The O-QPSK PHY shall have a receiver maximum input level greater than or equal to -20 dBm using the measurement defined in 11.2.5.

13.3.12 Receiver ED

The O-QPSK PHY shall provide the receiver ED measurement as described in 11.2.6.

13.3.13 LQI

The O-QPSK PHY shall provide the LQI measurement as described in 11.2.7.

14. Binary phase-shift keying (BPSK) PHY

14.1 PPDU format

The BPSK PHY shall use the PPDU format described in 13.1, except that the Preamble field is 32 symbols (4 octets).

14.2 Modulation and spreading

14.2.1 General

The BPSK PHY shall employ DSSS with BPSK used for chip modulation and differential encoding used for data symbol encoding.

14.2.2 BPSK PHY data rates

The data rate of the BPSK PHY shall be 20 kb/s when operating in the 868 MHz band and 40 kb/s when operating in the 915 MHz band.

14.2.3 Reference modulator

The functional block diagram of the reference modulator in Figure 14-1 is provided as a reference for specifying the BPSK PHY modulation and spreading functions. Each bit in the PPDU shall be processed through the differential encoding, bit-to-chip mapping, and modulation functions in octet-wise order, beginning with the Preamble field and ending with the last octet of the PHY Payload field.



Figure 14-1—BPSK reference modulator block diagram

14.2.4 Differential encoding

Differential encoding is the modulo-2 addition (exclusive or) of a raw data bit with the previous encoded bit. This is performed by the transmitter and can be described as follows:

$$E_n = R_n \oplus E_{n-1}$$

where

- R_n is the raw data bit being encoded
- E_n is the corresponding differentially encoded bit
- E_{n-1} is the previous differentially encoded bit

For each packet transmitted, R_1 is the first raw data bit to be encoded, and E_0 is assumed to be zero.

Conversely, the decoding process, as performed at the receiver, can be described as follows:

$$R_n = E_n \oplus E_{n-1}$$

For each packet received, E_1 is the first bit to be decoded, and E_0 is assumed to be zero.

14.2.5 Bit-to-chip mapping

Each input bit shall be mapped into a 15-chip PN sequence as specified in Table 14-1.

Table 14-1—Symbol-to-chip mapping

Input bits	Chip values ($c_0 c_1 \dots c_{14}$)
0	1 1 1 1 0 1 0 1 1 0 0 1 0 0 0
1	0 0 0 0 1 0 1 0 0 1 1 0 1 1 1

14.2.6 BPSK modulation

14.2.6.1 General

The chip sequences are modulated onto the carrier using BPSK with raised cosine pulse shaping (roll-off factor = 1) where a chip value of one corresponds to a positive pulse and a chip value of zero corresponds to a negative pulse. The chip rate is 300 kchip/s for the 868 MHz band and 600 kchip/s in the 915 MHz band.

14.2.6.2 Pulse shape

The raised cosine pulse shape (roll-off factor = 1) used to represent each baseband chip is described as follows:

$$p(t) = \begin{cases} \frac{\sin \pi t/T_c}{\pi t/T_c} \frac{\cos \pi t/T_c}{1 - 4t^2/T_c^2}, & t \neq 0 \\ 1, & t = 0 \end{cases}$$

14.2.6.3 Chip transmission order

During each symbol period, the least significant chip, c_0 , is transmitted first, and the most significant chip, c_{14} , is transmitted last.

14.3 BPSK PHY RF requirements

14.3.1 Operating frequency range

The BPSK PHY operates in the following frequency bands:

- 868.0–868.6 MHz
- 902–928 MHz

14.3.2 915 MHz band transmit PSD mask

The transmitted spectral products shall be less than the limits specified in Table 14-2. For the 915 MHz band, both relative and absolute limits, average spectral power shall be measured using a 100 kHz resolution

bandwidth. For the relative limit, the reference level shall be the highest average spectral power measured within ± 600 kHz of the carrier frequency.

Table 14-2—915 MHz band transmit PSD limits

Frequency band	Frequency	Relative limit	Absolute limit
915 MHz	$ f - f_c > 1.2$ MHz	-20 dB	-20 dBm

14.3.3 Symbol rate

The symbol rate of a BPSK PHY conforming to this standard shall be 20 ksymbol/s when operating in the 868 MHz band and 40 ksymbol/s when operating in the 915 MHz band with an accuracy of $\pm 40 \times 10^{-6}$.

14.3.4 Receiver sensitivity

Under the conditions specified in 11.1.8, a compliant device shall be capable of achieving a receiver sensitivity of -92 dBm or better.

14.3.5 Receiver interference rejection

This subclause applies only to the 915 MHz band because there is only one channel available in the 868 MHz band.

The minimum receiver interference rejection levels are given in Table 14-3.

Table 14-3—Minimum receiver interference rejection requirements for the 915 MHz BPSK PHYs

Frequency band	Adjacent channel rejection	Alternate channel rejection
915 MHz band	0 dB	30 dB

For the 915 MHz band, the adjacent channel is one on either side of the desired channel that is closest in frequency to the desired channel, and the alternate channel is one more removed from the adjacent channel. For example, when channel 5 is the desired channel, channel 4 and channel 6 are the adjacent channels, and channel 3 and channel 7 are the alternate channels.

The adjacent channel rejection shall be measured as follows: the desired signal shall be a compliant 915 MHz BPSK PHY signal, as defined by 14.2, of pseudo-random data. The desired signal is input to the receiver at a level 3 dB greater than the maximum allowed receiver sensitivity given in 14.3.4.

In either the adjacent or the alternate channel, a compliant 915 MHz BPSK PHY signal, as defined by 14.2, is input at the relative level specified in Table 14-3. The test shall be performed for only one interfering signal at a time. The receiver shall meet the error rate criteria defined in 11.1.8 under these conditions.

14.3.6 TX-to-RX turnaround time

The BPSK PHY shall have a TX-to-RX turnaround time as defined in 11.2.2.

14.3.7 RX-to-TX turnaround time

The BPSK PHY shall have an RX-to-TX turnaround time as defined in 11.2.3.

14.3.8 EVM

The BPSK PHY shall have EVM values of less than 35% when measured for 1000 chips using the measurement process defined in 11.2.4.

14.3.9 Transmit center frequency tolerance

The BPSK PHY transmit center frequency tolerance shall be $\pm 40 \times 10^{-6}$ maximum.

14.3.10 Transmit power

The BPSK PHY shall be capable of transmitting at a power level of at least -3 dBm.

14.3.11 Receiver maximum input level of desired signal

The BPSK PHY shall have a receiver maximum input level greater than or equal to -20 dBm using the measurement defined in 11.2.5.

14.3.12 Receiver ED

The BPSK PHY shall provide the receiver ED measurement as described in 11.2.6.

14.3.13 LQI

The BPSK PHY shall provide the LQI measurement as described in 11.2.7.

15. Chirp spread spectrum (CSS) PHY

15.1 CSS PPDU format

15.1.1 General

The CSS PPDU shall be formatted as illustrated in Figure 15-1.



Figure 15-1—Format of the CSS PPDU

The SHR field shall be formatted as illustrated in Figure 15-2.

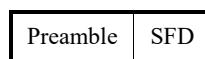


Figure 15-2—Format of the SHR

15.1.2 Preamble field

The Preamble field for 1 Mb/s consists of 8 chirp symbols, and the Preamble field for optional 250 kb/s consists of 20 chirp symbols as specified in Table 15-1. The preamble sequence from Table 15-1 should be applied directly to both the I input and the Q input of QPSK.

Table 15-1—Preamble sequence

Data rate	Preamble sequence
1 Mb/s	ones(0:31)
250 kb/s	ones(0:79)

where $\text{ones}(0:N)$ for integer number N is defined as a 1-by- N matrix of ones.

15.1.3 SFD field

SFD field bit sequences for the CSS PHY type are defined in Table 15-2. Different SFD sequences are defined for the two different data rates. An SFD sequence from Table 15-2 shall be applied directly to both inputs (I and Q) of the QPSK mapper. An SFD sequence starts with bit 0.

Table 15-2—CSS SFD field bit sequence

Data rate	Bit (0:15)
1 Mb/s	-1 1 1 1 -1 1 -1 -1 1 -1 -1 1 1 1 -1 -1
250 kb/s	-1 1 1 1 1 -1 1 -1 -1 1 -1 -1 -1 1 1

15.1.4 PHR field

The CSS PHR field shall be formatted as illustrated in Figure 15-3.

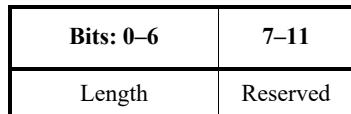


Figure 15-3—Format of the CSS PHR

The Length field is an unsigned integer and shall be set to the length of the PHY Payload field, in octets. The Length field shall be transmitted LSB first.

15.1.5 PHY Payload field

The PHY Payload field carries the PSDU.

15.2 Modulation and spreading

15.2.1 General

The CSS PHY uses CSS techniques in combination with DQPSK and 8-ary or 64-ary bi-orthogonal coding for 1 Mb/s data rate or 250 kb/s data rate, respectively. By using alternating time gaps in conjunction with sequences of chirp signals (subchirps) in different frequency subbands with different chirp directions, this CSS PHY provides subchirp sequence division as well as frequency division.

15.2.2 Data rates

The data rate of the CSS (2450 MHz) PHY shall be 1 Mb/s. An additional data rate of 250 kb/s shall be optional.

15.2.3 Reference modulator

The functional block diagram of the reference modulator in Figure 15-4 is provided as a reference for specifying the 2450 MHz CSS PHY modulation for both 1 Mb/s and optional 250 kb/s. All binary data contained in the PHR field and PHY Payload field shall be encoded using the modulation shown in Figure 15-4.

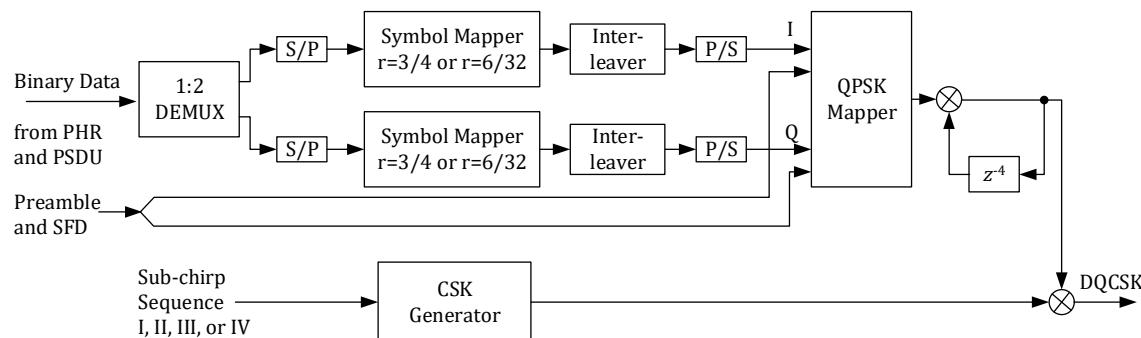


Figure 15-4—Differential bi-orthogonal quaternary-chirp-shift-keying modulator and spreading ($r = 3/4$ for 8-ary 1 Mb/s, $r = 3/16$ for 64-ary 250 kb/s)

15.2.4 De-multiplexer (DEMUX)

For each packet, the initial position of the DEMUX shown in Figure 15-4 shall be set to serve the I path (upper path). Thus, the first bit of the incoming stream of information bits of a packet shall be switched to the I path, and the second bit shall be switched to the Q path.

15.2.5 Serial-to-parallel mapping

By using two serial-to-parallel converters, the substreams are independently partitioned into sets of bits to form data symbols. For the mandatory data rate of 1 Mb/s, a data symbol shall consist of three bits. Within the binary data symbol (b0,b1,b2), the first input data bit for each of I and Q is assigned b0, and the third input data bit is assigned b2. For the optional data rate of 250 kb/s, a data symbol shall consist of 6 bits. Within the binary data symbol (b0,b1,b2,b3,b4,b5), the first input data bit for each of I and Q is assigned b0, and the sixth input data bit is assigned b5.

15.2.6 Data-symbol-to-bi-orthogonal-codeword mapping

Each 3-bit data symbol shall be mapped onto a 4-chip bi-orthogonal codeword (c0, c1, c2, c3) for the 1 Mb/s data rate as specified in Table 15-3. Each 6-bit data symbol shall be mapped onto a 32-chip bi-orthogonal codeword (c0, c1, c2, ..., c31) for the optional 250 kb/s data rate as specified in Table 15-4.

Table 15-3—8-ary bi-orthogonal mapping ($r = 3/4$, 1 Mb/s)

Data symbol	Codeword (c0 c1 c2 c3)
0	1 1 1 1
1	1 -1 1 -1
2	1 1 -1 -1
3	1 -1 -1 1
4	-1 -1 -1 -1
5	-1 1 -1 1
6	-1 -1 1 1
7	-1 1 1 -1

Table 15-4—64-ary bi-orthogonal mapping ($r = 3/16$, 250 kb/s)

Data symbol	Codeword (c0 c1 c2 ... c31)
0	1 1
1	1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1
2	1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1
3	1 -1 -1 1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1
4	1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1

Table 15-4—64-ary bi-orthogonal mapping ($r = 3/16$, 250 kb/s) (continued)

Data symbol	Codeword (c0 c1 c2 ... c31)
5	1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1
6	1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1
7	1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1
8	1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 -1
9	1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 -1
10	1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 1 -1 -1 1 1
11	1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1
12	1 1 1 1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1
13	1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1
14	1 1 -1 -1 -1 1 1 -1 -1 -1 1 1 1 1 1 1 -1 -1 1 1 -1 -1 -1 1 1 -1 -1 -1 1 1 1 1 1 1 -1 -1
15	1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 1 -1 1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 1 -1 1 -1 1
16	1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1
17	1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1
18	1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 1 1 -1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 1 -1 1 1 -1
19	1 -1 -1 1 1 -1 -1 1 1 -1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 -1 -1 1 1 -1 -1 1 1 -1
20	1 1 1 1 -1 -1 -1 -1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1
21	1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 1
22	1 1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 -1 1 -1 1 -1 -1 1 1 1 1 -1 -1 -1 1 -1 1 1 1 1 -1 -1
23	1 -1 -1 1 -1 1 1 -1 1 -1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1
24	1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 1
25	1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 1

Table 15-4—64-ary bi-orthogonal mapping ($r = 3/16$, 250 kb/s) (continued)

Data symbol	Codeword (c0 c1 c2 ... c31)
26	1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 -1
27	1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 1 -1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1
28	1 1 1 1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 1 -1 -1 -1 -1
29	1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 1 -1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1
30	1 1 -1 -1 -1 1 1 -1 -1 1 1 1 1 1 1 1 -1 -1 -1 -1 1 1 1 -1 -1 1 1 -1 -1 1 -1 -1 -1 1 1 1
31	1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 -1 1 1 -1
32	-1 -1
33	-1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 1
34	-1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1
35	-1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 1 1 1 -1
36	-1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1
37	-1 1 -1 1 1 -1 1 -1 -1 1 -1 1 -1 1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 -1 1 1 -1 1 1 -1 1 -1
38	-1 -1 1 1 1 1 -1 -1 -1 -1 -1 1 1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 -1 1 1 1 1 1 1 -1 -1
39	-1 1 1 -1 1 -1 -1 1 -1 1 -1 1 1 -1 1 -1 -1 1 1 -1 1 1 -1 1 -1 -1 1 -1 1 -1 1 1 -1 1 -1 -1 1 1
40	-1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 1 1 1
41	-1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1
42	-1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 1 1 -1 -1 -1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 1 1 -1 -1
43	-1 1 1 -1 -1 1 1 -1 1 -1 1 -1 -1 1 1 -1 1 -1 1 -1 -1 1 1 -1 -1 1 1 -1 1 -1 1 -1 -1 1 1 -1 1 -1 1 -1
44	-1 -1 -1 -1 1 1 1 1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 1 1 1 1 -1 -1 -1 -1
45	-1 1 -1 1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1
46	-1 -1 1 1 1 1 -1 -1 1 1 -1 1 1 -1 -1 -1 -1 1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 -1 1 1 -1 -1 -1 -1 1 1 1

Table 15-4—64-ary bi-orthogonal mapping ($r = 3/16$, 250 kb/s) (continued)

Data symbol	Codeword (c0 c1 c2 ... c31)
47	-1 1 1 -1 1 -1 -1 1 1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 -1 -1 1 1 1 -1 -1 1 -1 1 1 -1
48	-1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
49	-1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1
50	-1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 1 1 -1
51	-1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 1
52	-1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 1 -1 -1 -1 1 1 1 1 1 1 -1 -1 -1 1 1 1
53	-1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 1 -1 -1 1 -1 1 -1
54	-1 -1 1 1 1 -1 -1 -1 -1 -1 1 1 1 1 1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 1 1 -1 1 1
55	-1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 -1 1 1 -1
56	-1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1
57	-1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 -1 1 -1
58	-1 -1 1 1 -1 -1 1 1 1 1 -1 -1 1 1 1 -1 1 1 -1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 1 -1 -1 -1 1 1 -1
59	-1 1 1 -1 -1 1 1 -1 1 -1 -1 -1 1 1 -1 1 1 -1 1 1 -1 -1 1 1 -1 -1 1 -1 1 -1 1 1 -1 -1 1 1 -1
60	-1 -1 -1 -1 1 1 1 1 1 1 1 1 1 1 1 -1 -1 -1 -1 1 1 1 1 -1 -1 -1 -1 -1 -1 -1 -1 -1 1 1 1 1 1
61	-1 1 -1 1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 -1 1 -1 1 -1 1 1 -1 1 -1
62	-1 -1 1 1 1 1 -1 -1 1 1 -1 -1 -1 -1 -1 1 1 1 1 1 -1 -1 -1 -1 1 1 -1 -1 -1 1 1 1 1 -1 -1
63	-1 1 1 -1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 -1 1 1 -1 1 1 -1 -1 1 -1 1

15.2.7 Parallel-to-serial converter and QPSK symbol mapping

Each bi-orthogonal codeword shall be converted to a serial chip sequence. Within each 4-chip codeword (c_0, c_1, c_2, c_3) for the 1 Mb/s data rate, the least significant chip c_0 is processed first, and the most significant chip c_3 is processed last, for both I and Q. Within each 32-chip codeword ($c_0, c_1, c_2, \dots, c_{31}$) for the 250 kb/s data rate, the least significant chip c_0 is processed first, and the most significant chip c_{31} is processed last, for both I and Q. Each pair of I and Q chips shall be mapped onto a QPSK symbol as specified in Table 15-5.

Table 15-5—QPSK symbol mapping

Input chips ($I_{n,k} Q_{n,k}$)	Magnitude	Output phase (rad)
1, 1	1	0
-1, 1	1	$\pi/2$
1, -1	1	$-\pi/2$
-1, -1	1	π

15.2.8 DQPSK coding

The stream of QPSK symbols shall be differentially encoded by using a differential encoder with a QPSK symbol feedback memory of length 4. (In other words, the phase differences between QPSK symbol 1 and 5, 2 and 6, 3 and 7, 4 and 8, and so on are computed.) For a detailed explanation of the index variables n and k , as described in 15.3.4.

DQPSK output:

$$e^{j\theta_{n,k}} = e^{j\theta_{n-1,k}} \times e^{j\varphi_{n,k}}$$

where

$e^{j\varphi_{n,k}}$ is DQPSK input

$e^{j\theta_{n-1,k}}$ is stored in feedback memory

For every packet, the initial values of all four feedback memory stages of the differential encoder shall be set as follows:

$$e^{j\pi/4}$$

15.2.9 DQPSK-to-DQCSK modulation

The stream of DQPSK symbols shall be modulated onto the stream of subchirps that is generated by the chirp-shift keying (CSK) generator. The effect of the differential quadrature chirp-shift keying (DQCSK) modulation shall be that each subchirp is multiplied with a DQPSK value that has unit magnitude and has constant phase for the duration of the subchirp. An example of this operation can be found in 15.3.7.

15.2.10 CSK generator

The CSK generator shall periodically generate one of the four defined subchirp sequences (chirp symbols) as specified in 15.3.4. Since each chirp symbol consists of four subchirps, the subchirp rate is four times higher than the chirp symbol rate.

15.2.11 Bit interleaver

The bit interleaver is applied only for the optional data rate of 250 kb/s. The 32-chip bi-orthogonal codewords for the optional 250 kb/s data rate are interleaved prior to the parallel to serial converter. Bit interleaving provides robustness against double intra-symbol errors caused by the differential detector. The interleaver permutes the chips across two consecutive codewords for each of I and Q, independently.

The memory of the interleaver shall be initialized with zeros before the reception of a packet.

The data stream going into the interleaver shall be padded with zeros if the number of octets to be transmitted does not align with the bounds of the interleaver blocks.

The input-output relationship of this interleaver shall be as follows:

Input:

```
even-symbol (c0, c1, c2, c3, c4, c5, c6, c7, c8, c9, c10, c11, c12, c13, c14, c15,  
c16, c17, c18, c19, c20, c21,c22,c23, c24, c25, c26, c27, c28, c29, c30, c31)  
odd-symbol (d0, d1, d2, d3, d4, d5, d6, d7, d8, d9, d10, d11, d12, d13, d14, d15,  
d16, d17, d18, d19, d20, d21, d22, d23, d24, d25, d26, d27, d28, d29, d30, d31)
```

Output:

```
even-symbol (c0, c1, c2, c3, d20, d21, d22, d23, c8, c9, c10, c11, d28, d29, d30, d31,  
c16, c17, c18, c19, d4, d5, d6, d7, c24, c25, c26, c27, d12, d13, d14, d15)  
odd-symbol (d0, d1, d2, d3, c20, c21, c22, c23, d8, d9, d10, d11, c28, c29, c30, c31,  
d16, d17, d18, d19, c4, c5, c6, c7, d24, d25, d26, d27, c12, c13, c14, c15)
```

NOTE—As shown in Figure 15-4, coding is applied to every bit following the SFD. The first codeword generated is counted as zero and thus is even.

15.3 Waveform and subchirp sequences

15.3.1 General

Four individual chirp signals, here called subchirps, shall be concatenated to form a full chirp symbol (subchirp sequence), which occupies two adjacent frequency subbands. Four different subchirp sequences are defined. Each subchirp is weighted with a raised cosine window in the time domain.

15.3.2 Graphical presentation of chirp symbols (subchirp sequences)

Four different sequences of subchirp signals are available for use. Figure 15-5 shows the four different chirp symbols (subchirp sequences) as time frequency diagrams. It can be seen that four subchirps, which have either a linear down-chirp characteristic or a linear up-chirp characteristic, and a center frequency, which has either a positive or a negative frequency offset, are concatenated. The frequency discontinuities between subsequent chirps will not affect the spectrum because the signal amplitude will be zero at these points.

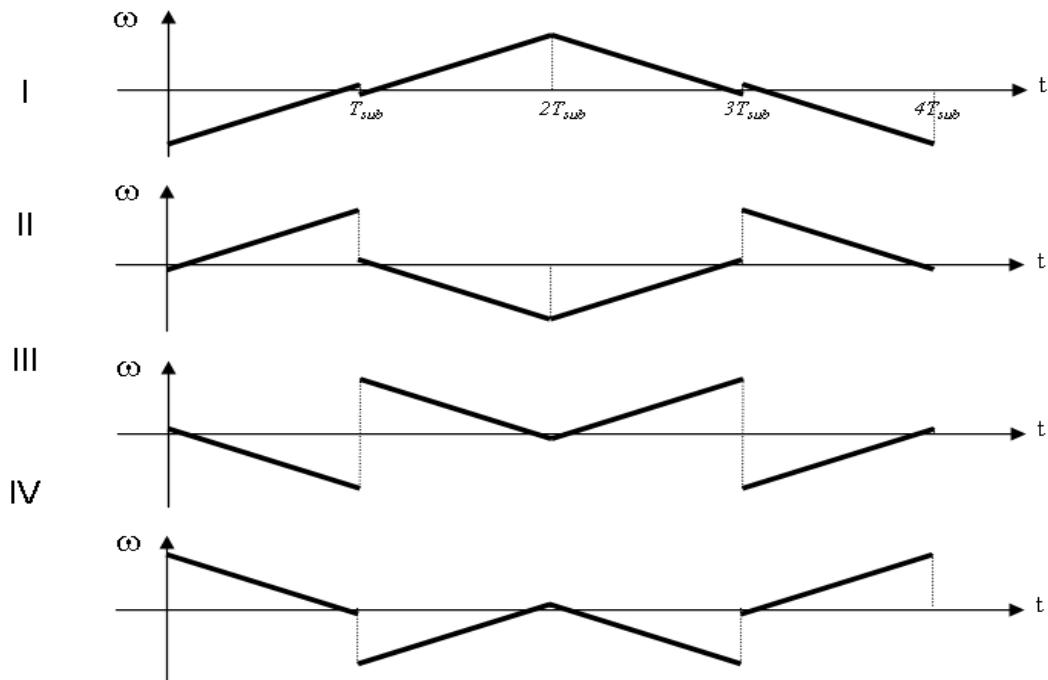


Figure 15-5—Four different combinations of subchirps

15.3.3 Active usage of time gaps

In conjunction with the subchirp sequence, different pairs of time gaps are defined. The time gaps are chosen to make the four sequences even closer to being orthogonal. The time gaps shall be applied alternatively between subsequent chirp symbols as shown in Figure 15-6. The values of the time gaps are calculated from the timing parameters specified in Table 15-8.

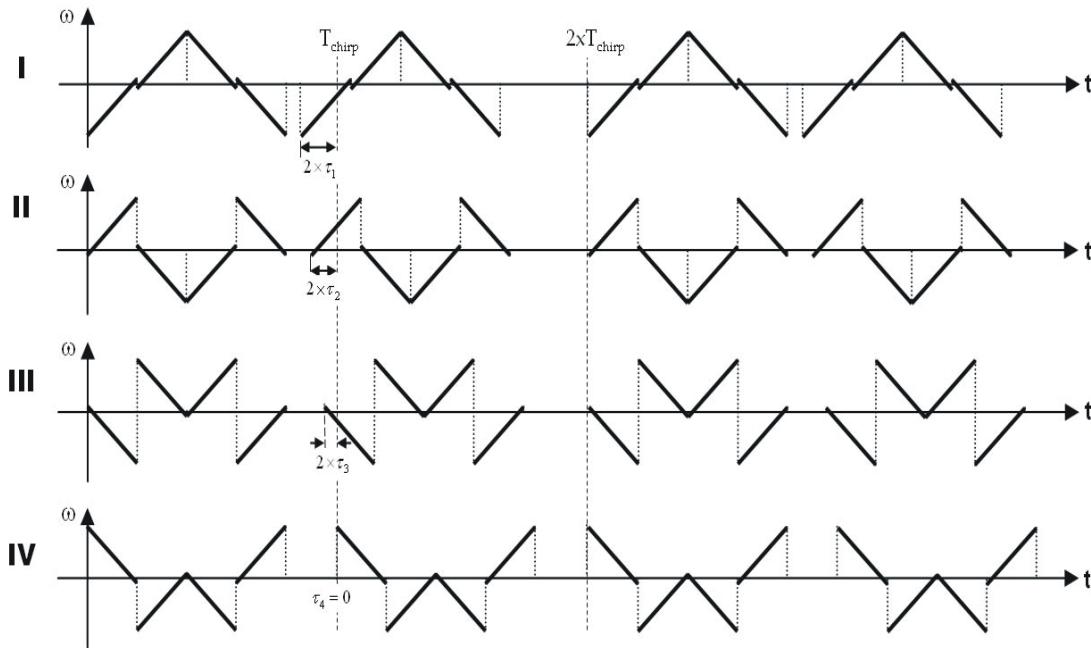


Figure 15-6—Four different time-gap pairs for the four different subchirp sequences

15.3.4 Mathematical representation of the continuous time CSS base-band signal

The mathematical representation of the continuous time-domain base-band signal $\tilde{s}^m(t)$ built of chirp symbols (subchirp sequences) as shown in Figure 15-5 with alternating time gaps as shown in Figure 15-6. The subchirp sequence with its associated time gap is defined to be a chirp symbol as follows:

$$\begin{aligned}\tilde{s}^m(t) &= \sum_{n=0}^{\infty} \tilde{s}^m(t, n) \\ &= \sum_{n=0}^{\infty} \sum_{k=1}^4 \tilde{c}_{n,k} \exp \left[j \left(\hat{\omega}_{k,m} + \frac{\mu}{2} \xi_{k,m} (t - T_{n,k,m}) \right) (t - T_{n,k,m}) \right] \times P_{RC}(t - T_{n,k,m})\end{aligned}$$

where $m = 1, 2, 3, 4$ (I, II, III, and IV in Figure 15-5) defines which of the four different possible chirp symbols (subchirp sequences) is used, and $n = 0, 1, 2, \dots$, is the sequence number of the chirp symbols.

The $\tilde{c}_{n,k}$ is the sequence of the complex data that consists of in-phase data $a_{n,k}$ and quadrature-phase data $b_{n,k}$ as the output of DQPSK coding.

The possible values of $a_{n,k}$ and $b_{n,k}$ are $+1$ or -1 .

$$\tilde{c}_{n,k} = a_{n,k} + j b_{n,k}$$

where

- | | |
|-------------------------------|---|
| n | is the sequence number of chirp symbols |
| $k = 0, 1, 2, \text{ and } 3$ | is the subchirp index |
| j | is $\sqrt{-1}$ |

$\hat{\omega}_{k,m} = 2\pi \times f_{k,n}$ are the center frequencies of the subchirp signals. This value depends on m and $k = 1, 2, 3, 4$, which defines the subchirp number in the subchirp sequence.

$T_{n,k,m}$ defines the starting time of the actual subchirp signal to be generated. It is determined by T_{chirp} , which is the average duration of a chirp symbol, and by T_{sub} , which is the duration of a subchirp signal.

$$T_{n,k,m} = \left(k + \frac{1}{2}\right) T_{\text{sub}} + n T_{\text{chirp}} - (1 - (-1)^n) \tau_m$$

The constant μ defines the characteristics of the subchirp signal. A value of $\mu = 2\pi \times 7.3158 \times 10^{12} [\text{rad/s}^2]$ shall be used.

The function P_{RC} , which is defined in 15.3.5, is a windowing function that is equal to zero at the edges and outside of the subchirp centered at time zero.

The constant τ_m is either not added or added twice and thus determines (but is not identical to) the time gap that was applied between two subsequent subchirp sequences as shown in Figure 15-6.

Table 15-6 shows the values for the subband center frequencies, Table 15-7 shows the subchirp directions, and Table 15-8 shows the timing parameters. These time and frequency parameters are assumed to be derived from a reference crystal in a locked manner. In other words, any relative errors in chirp subband center frequencies, chirp rate, and time gaps are equal.

Table 15-6—Subband center frequencies, $f_{k,m}$ (MHz, numerical parameters)

$m \setminus k$	1	2	3	4
1	$f_c - 3.15$	$f_c + 3.15$	$f_c + 3.15$	$f_c - 3.15$
2	$f_c + 3.15$	$f_c - 3.15$	$f_c - 3.15$	$f_c + 3.15$
3	$f_c - 3.15$	$f_c + 3.15$	$f_c + 3.15$	$f_c - 3.15$
4	$f_c + 3.15$	$f_c - 3.15$	$f_c - 3.15$	$f_c + 3.15$

Table 15-7—Subchirp directions, $\xi_{k,m}$, numerical parameters

$m \setminus k$	1	2	3	4
1	+1	+1	-1	-1
2	+1	-1	+1	-1
3	-1	-1	+1	+1
4	-1	+1	-1	+1

Table 15-8—Timing parameters for baseband signal

Symbol	Value	Multiple of 1/32 MHz
T_{chirp}	6 μs	192
T_{sub}	1.1875 μs	38
τ_1	468.75 μs	15
τ_2	312.5 ns	10
τ_3	156.25 ns	5
τ_4	0 ns	0

15.3.5 Raised cosine window for chirp pulse shaping

The raised-cosine time window described here shall be used to shape the subchirp. The raised cosine window $P_{\text{RC}}(t)$ is applied to every subchirp signal in the time domain, as illustrated in Figure 15-7.

$$P_{\text{RC}}(t) = \begin{cases} 1 & |t| \leq \frac{(1-\alpha)T_{\text{sub}}}{(1+\alpha)/2} \\ \frac{1}{2} \left[1 + \cos \left(\frac{(1+\alpha)\pi}{\alpha T_{\text{sub}}} \left(|t| - \frac{(1-\alpha)T_{\text{sub}}}{(1+\alpha)/2} \right) \right) \right] & \frac{(1-\alpha)T_{\text{sub}}}{(1+\alpha)/2} < |t| \leq \frac{T_{\text{sub}}}{2} \\ 0 & |t| > \frac{T_{\text{sub}}}{2} \end{cases}$$

where $\alpha = 0.25$.

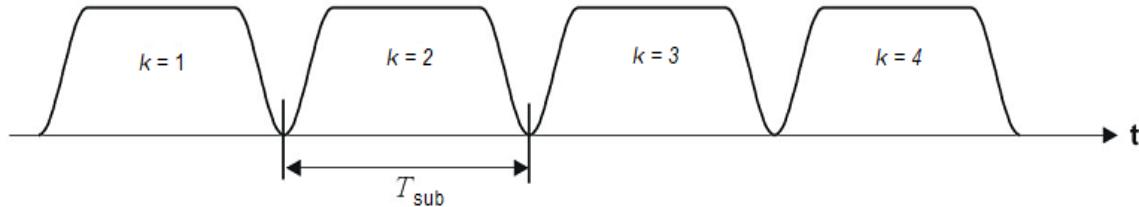


Figure 15-7—Subchirp time-domain pulse shaping

15.3.6 Subchirp transmission order

During each chirp symbol period, subchirp 1 ($k = 1$) is transmitted first, and subchirp 4 ($k = 4$) is transmitted last.

15.3.7 Example of CSK signal generation

An example for the modulation of one chirp symbol is provided in this subclause to illustrate each step from DEMUX to the output of the reference modulator as shown in Figure 15-4. The scenario parameters are as follows:

- The initial values of all four feedback memory stages of the differential encoder are set to $e^{(j\pi)/4}$.
- The data bit rate is 1 Mb/s.

Input binary data:

0 1 0 1 1 0

Demux:

I-path: 0 0 1

Q-path: 1 1 0

Serial-to-parallel mapping:

I-path: {1 0 0}

Q-path: {1 1 0}

Bi-orthogonal mapping ($r = 3/4$):

I-path: 1 -1 1 -1

Q-path: -1 -1 1 1

Parallel-to-serial and QPSK symbol mapping:

Mapper input: $(1-j), (-1-j), (1+j), (-1+j)$

QPSK output phase: $-\pi/2, \pi, 0, \pi/2$

D-QPSK coding:

Initial phase of four feedback memory for D-QPSK: all $\pi/4$

D-QPSK coder output phase: $-\pi/4, -3\pi/4, \pi/4, 3\pi/4$

D-QPSK-to-D-QCSK modulation output and subchirp sequence of D-QCSK output:

$[\exp(-j\pi/4) \times \text{subchirp}(k=1), \exp(-j3\pi/4) \times \text{subchirp}(k=2), \exp(j\pi/4) \times \text{subchirp}(k=3), \exp(j3\pi/4) \times \text{subchirp}(k=4)]$

15.4 CSS RF requirements

15.4.1 General

In addition to meeting regional regulatory requirements, CSS devices operating in the 2450 MHz band shall also meet the requirements in this subclause.

15.4.2 Transmit power spectral density (PSD) mask and signal tolerance

The transmitted spectral power density of a CSS signal $s(t)$ shall be within the relative limits specified in the template shown in Figure 15-8. The average spectral power shall be made using 100 kHz resolution bandwidth and a 1 kHz video bandwidth. For the relative limit, the reference level shall be the highest average spectral power measured within ± 11 MHz of the carrier frequency. Specifically, the normalized frequency spectrum to the peak value in the signal bandwidth $|f - f_c| \leq 7$ MHz shall be less than or equal to -30 dB in the stop band $11 \text{ MHz} \leq |f - f_c| \leq 22$ MHz and shall be less than or equal to -50 dB in the stop band $|f - f_c| > 22$ MHz. For testing the transmitted spectral power density, a $2^{15} - 1$ pseudo-random binary sequence (PRBS) shall be used as input data.

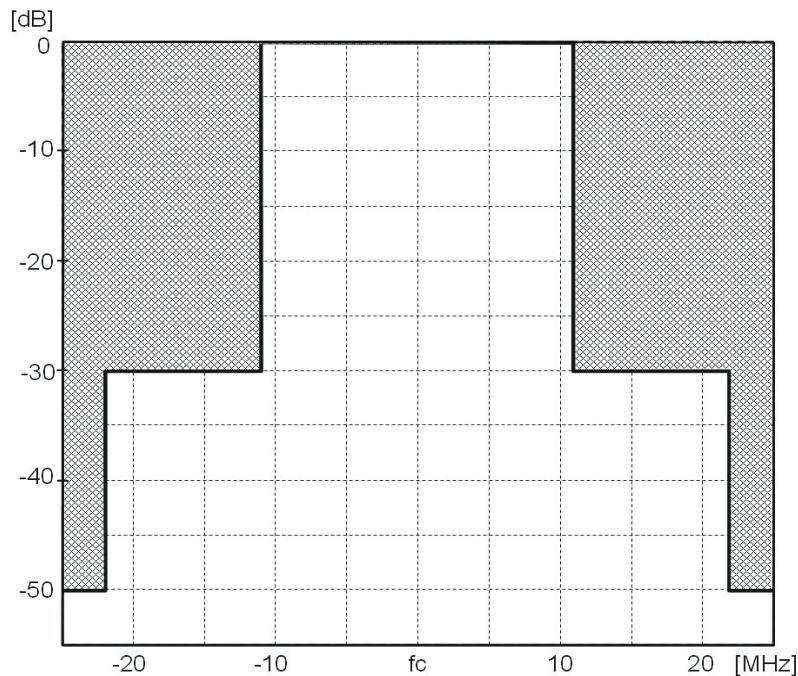


Figure 15-8—Transmit PSD mask

As additional criteria for the compliance of a CSS signal, the mean square error shall be used. Let $s(t)$ be the baseband CSS signal that is given in 15.3.4. Then the implemented signal, $s_{impl}(t)$, shall satisfy the following equation:

$$\text{mmse} = \min_{A, \tau_d, \phi} \left(\frac{\int_0^T |s^m(t) - A \times s_{impl}^m(t - \tau_d) e^{j\phi}|^2 dt}{\int_0^T |s^m(t)|^2 dt} \right) \leq 0.005$$

where the constants A , τ_d , and φ are used to minimize the mean squared error. The constant T_{chirp} is the period of the CSS symbol. The $c_{n,k}$ of $s(t)$ is the constant data ($1+j$) for the measurement for all n and k .

15.4.3 Symbol rate

The 2450 MHz PHY DQCSK symbol rate shall be 166.667 ksymbol/s (1/6 Msymbol/s) $\pm 40 \times 10^{-6}$.

15.4.4 Receiver sensitivity

Under the conditions specified in 11.1.8, a compliant device shall be capable of achieving a receiver sensitivity of -85 dBm or better for 1 Mb/s and -91 dBm or better for 250 kb/s.

15.4.5 Receiver interference rejection

Table 15-9 gives minimum receiver interference rejection levels. A nonoverlapping adjacent channel is defined to have a center frequency offset of 25 MHz. A nonoverlapping alternate channel is defined to have a center frequency offset of 50 MHz. The adjacent channel rejection shall be measured as follows: The desired signal shall be a compliant 2450 MHz CSS signal of pseudo-random data. The desired signal is input to the receiver at a level 3 dB above the maximum allowed receiver sensitivity given in 15.4.4. In the adjacent or the alternate channel, a CSS signal of the same or a different subchirp sequence as the victim channel is input at the relative level specified in Table 15-9. The test shall be performed for only one interfering signal at a time. The receiver shall meet the error rate criteria defined in Table 11.1.8.

Table 15-9—Minimum receiver interference rejection levels for 2450 MHz CSS PHY

Data rate	Nonoverlapping adjacent channel rejection (25 MHz offset) (dB)	Nonoverlapping alternate channel rejection (50 MHz offset) (dB)
1 Mb/s	34	48
250 kb/s (optional)	38	52

15.4.6 TX-to-RX turnaround time

The TX-to-RX turnaround time shall be less than or equal to $aTurnaroundTime$, as defined in 12.2.

The TX-to-RX turnaround time is defined as the shortest time possible at the air interface from the trailing edge of the last chirp (of the last symbol) of a transmitted PPDU to the leading edge of the first chirp (of the first symbol) of the next received PPDU.

The TX-to-RX turnaround time shall be less than or equal to the RX-to-TX turnaround time.

15.4.7 RX-to-TX turnaround time

The RX-to-TX turnaround time shall be less than or equal to $aTurnaroundTime$, as defined in 12.2.

The RX-to-TX turnaround time is defined as the shortest time possible at the air interface from the trailing edge of the last chirp (of the last symbol) of a received PPDU to the leading edge of the first chirp (of the first symbol) of the next transmitted PPDU.

15.4.8 Transmit center frequency tolerance

The CSS PHY transmit center frequency tolerance shall be $\pm 40 \times 10^{-6}$ maximum.

15.4.9 Transmit power

The CSS PHY shall be capable of transmitting at a power level of at least -3 dBm.

15.4.10 Receiver maximum input level of desired signal

The CSS PHY shall have a receiver maximum input level greater than or equal to -20 dBm using the measurement defined in 11.2.5.

15.4.11 Receiver ED

The CSS PHY shall provide the receiver ED measurement as described in 11.2.6.

15.4.12 LQI

The CSS PHY shall provide the LQI measurement as described in 11.2.7.

16. HRP UWB PHY

16.1 General

The HRP UWB PHY waveform is based upon an impulse radio signaling scheme using band-limited pulses. The HRP UWB PHY supports the following three independent bands of operation:

- *The sub-gigahertz band*, which consists of a single channel and occupies the spectrum from 249.6 MHz to 749.6 MHz.
- *The low band*, which consists of four channels and occupies the spectrum from 3.1 GHz to 4.8 GHz.
- *The high band*, which consists of 11 channels and occupies the spectrum from 6.0 GHz to 10.6 GHz.

Within each channel, there is support for at least two complex channels that have unique length 31 preamble codes. The combination of a channel and a preamble code is termed a *complex channel*. A compliant device shall implement support for at least one of the channels (0, 3, or 9) in Table 16-27. In addition, each device shall support the two unique length 31 preamble codes for the implemented channels as defined in Table 16-7. Support for the other channels listed in Table 16-27 is optional.

A combination of BPM and BPSK is used to support both coherent and noncoherent receivers using a common signaling scheme. The combined BPM-BPSK is used to modulate the symbols, with each symbol being composed of an active burst of UWB pulses. The various data rates are supported through the use of variable-length bursts. Figure 16-1 shows the sequence of processing steps used to create and modulate an HRP UWB PPDU. The sequence of steps indicated here for the transmitter is used as a basis for explaining the creation of the HRP UWB PHY waveform specified in the PHY of this clause.

NOTE—The receiver portion of Figure 16-1 is informative and meant only as a guide to the essential steps that any compliant HRP UWB receiver needs to implement in order to successfully decode the transmitted signal.

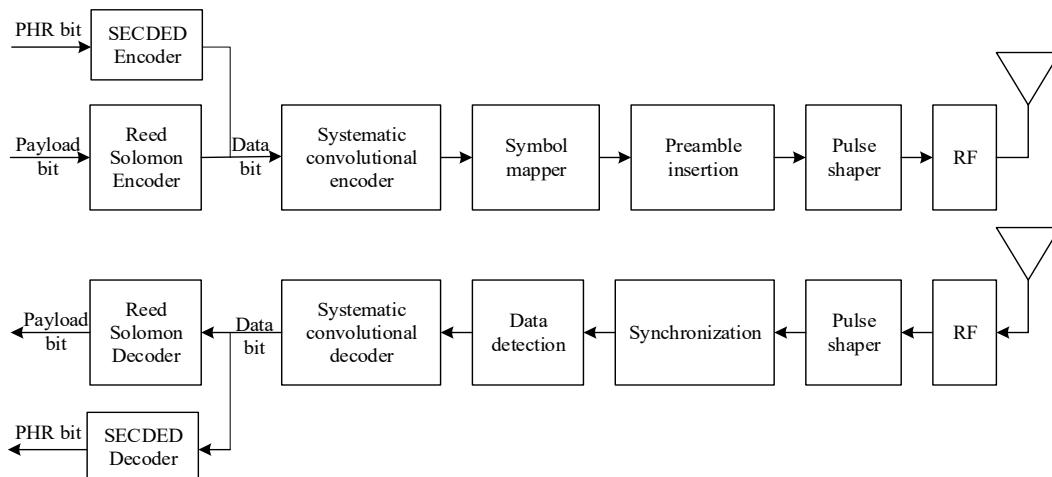


Figure 16-1—HRP UWB PHY signal flow

For the HRP UWB PHY, where MAC timing is specified in symbols, the duration of a preamble symbol (T_{psym}) is used.

The HRP UWB PHY also includes optional modes to give reduced on-air time for higher density/lower power operation, and where the frame includes a ciphered sequence, denoted as the scrambled timestamp

sequence (STS), to increase the integrity and accuracy of ranging measurements. A device incorporating these modes is referred to as an HRP-ERDEV. These modes require coherent receiver techniques.

An HRP-ERDEV shall support the following mandatory functionalities:

- Operation at the nominal 64 MHz PRF is referred to as the base pulse repetition frequency (BPRF) mode.

NOTE—By omitting the STS, the BPRF mode packet format reduces to a legacy packet format, which enables interworking.
- Operation at a higher PRF than the BPRF mode, referred to as the HPRF mode.

16.2 HRP UWB PPDU format

16.2.1 General

Figure 16-2 shows the format for the HRP UWB PPDU.

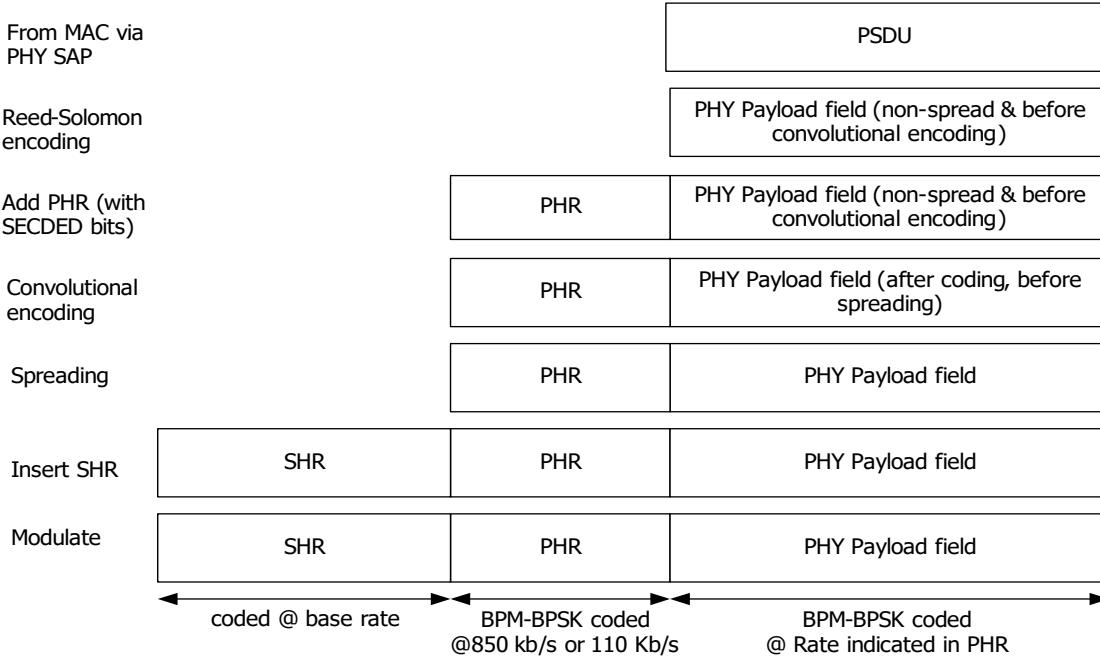


Figure 16-2—HRP UWB PPDU encoding process

Each HRP UWB-compliant device shall support the length 31 preamble codes specified in Table 16-7 and the two base rates corresponding to the two mandatory PRFs result for this code length. The mandatory SHR base rates are, therefore, 1.01 Msymbol/s and 0.25 Msymbol/s as indicated in Table 16-5.

The PHR is sent at 850 kb/s for all data rates greater than or equal to 850 kb/s and at 110 kb/s for the data rate of 110 kb/s. The PSDU is sent at the desired information data rate as defined in Table 16-4.

The HRP-ERDEV shall support transmission and reception of packets as specified in Table 16-1. Figure 16-3 provides an informative depiction of the STS position in the PPDU as well as the position of the RMARKER as defined in 10.29.1.

Table 16-1—PPDU STS packet structure configurations

STS packet configuration specifier value (see note)	Position of the STS in the PPDU	Support
0	There is no STS field included in the PPDU.	Mandatory
1	The STS field is placed immediately after the SFD field and before the PHR field.	Mandatory
2	The STS field is placed after the PHY Payload field.	Optional
3	The STS field is placed immediately after the SFD field and no PHR or Data fields are included.	Mandatory

NOTE—The STS packet configuration specifier value in Table 16-1 applies to the TxStsPacketStructure and RxStsPacketStructure parameters of the MLME-STS.request primitive specified in 10.29.9.4.1 and to the *phyHrpUwbStsTxPacketConfig* and *phyHrpUwbStsRxPacketConfig* attributes.

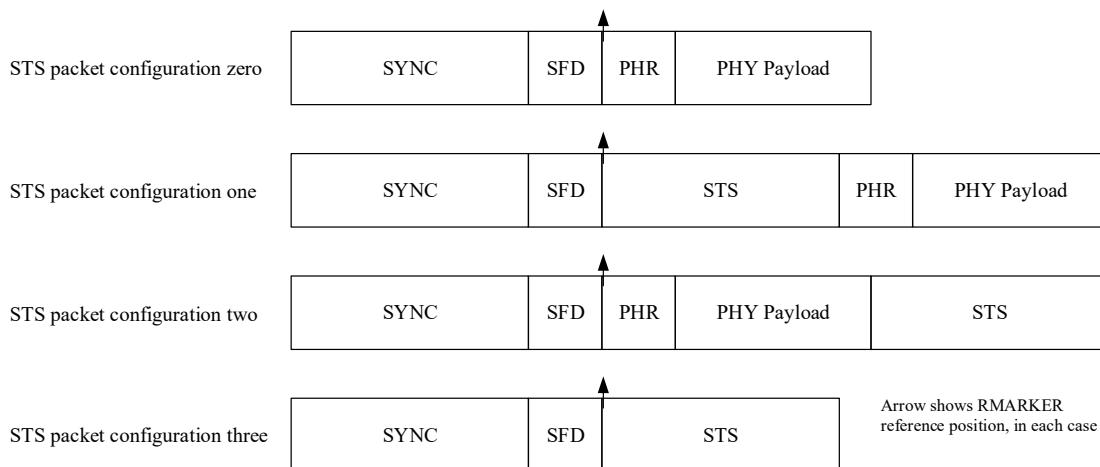


Figure 16-3—HRP-ERDEV PPDU formats with RMARKER position

16.2.2 PPDU encoding process

The encoding process is composed of many steps, as illustrated in Figure 16-2. The details of these steps are fully described in later subclauses, as noted in the following list:

- Perform Reed-Solomon encoding on the PSDU as described in 16.3.3.2.
- Produce the PHR as described in 16.2.7, including the single error correct, double error detect (SEC-DED) field and prepend to the PSDU.
- Perform further convolutional coding as described in 16.3.3.3. Note that in some instances at the 27 Mb/s data rate, the convolutional encoding of the PHY Payload field is effectively bypassed and two data bits are encoded per BPM-BPSK symbol.
- For the HPRF mode, modulate and spread the PHR and PSDU as described in 16.3.4. For the BPRF mode, modulate the PHR using BPM-BPSK at 850 kb/s (or optionally at 6.8 Mb/s). In all other cases modulate and spread PSDU according to the method described in 16.3.1 and 16.3.2, where the PHR is modulated using BPM-BPSK at either 850 kb/s or 110 kb/s, and the PHY Payload field is modulated at the rate specified in the PHR.

- e) Produce the SHR field from the SYNC field, as described in 16.2.6.2, and the SFD field, as described in 16.2.6.3.
- f) For HRP-ERDEV, produce the STS as described in 16.2.9 according to the setting of the *phyHrpUwbStsTxPacketConfig*, *phyHrpUwbStsTxSegLen*, and *phyHrpUwbStsTxSegNum* attributes.

Table 16-2 and Table 16-3 show how the PHR field, H_0 – H_{18} , PHY Payload field, D_0 – D_{N-1} , and Tail field, T_0 – T_1 , are mapped onto the symbols. In these tables, the polarity bit column operation is an XOR. The tables also show when the transition from the header bit rate to the data bit rate takes place.

NOTE—The delay line of the convolutional code is initialized to zero. For this reason, the position bit of Symbol 0 is always zero.

Table 16-2—Mapping of PHR field bits, PHY Payload field bits, and Tail field bits onto symbols with Viterbi rate 0.5

Symbol #	Input data	Position bit	Polarity bit	
0	H_0	0	H_0	21 symbols of PHY header at the PHR symbol rate
1	H_1	H_0	H_1	
2	H_2	H_1	$H_0 \oplus H_2$	
3	H_3	H_2	$H_1 \oplus H_3$	
...	
16	H_{16}	H_{15}	$H_{14} \oplus H_{16}$	
17	H_{17}	H_{16}	$H_{15} \oplus H_{17}$	
18	H_{18}	H_{17}	$H_{16} \oplus H_{18}$	
19	D_0	H_{18}	$H_{17} \oplus D_0$	
20	D_1	D_0	$H_{18} \oplus D_1$	
21	D_2	D_1	$D_0 \oplus D_2$	
...	
$N+17$	D_{N-2}	D_{N-3}	$D_{N-4} \oplus D_{N-2}$	
$N+18$	D_{N-1}	D_{N-2}	$D_{N-3} \oplus D_{N-1}$	
$N+19$	T_0	D_{N-1}	$D_{N-2} \oplus T_0$	
$N+20$	T_1	T_0	$D_{N-1} \oplus T_1$	

Table 16-3—Mapping of PHR field bits, PHY Payload field bits, and Tail field bits onto symbols with Viterbi rate 1

Symbol #	Input data	Position bit	Polarity bit	
0	H ₀	0	H ₀	21 symbols of PHY header at the PHR symbol rate
1	H ₁	H ₀	H ₁	
2	H ₂	H ₁	H ₀ ⊕ H ₂	
3	H ₃	H ₂	H ₁ ⊕ H ₃	
...	
16	H ₁₆	H ₁₅	H ₁₄ ⊕ H ₁₆	
17	H ₁₇	H ₁₆	H ₁₅ ⊕ H ₁₇	
18	H ₁₈	H ₁₇	H ₁₆ ⊕ H ₁₈	
19	T ₀	H ₁₈	H ₁₇ ⊕ T ₀	
20	T ₁	T ₀	H ₁₈ ⊕ T ₁	
21	D ₀ , D ₁	D ₀	D ₁	1/2 N symbols of data at the data symbol rate
...	D ₂ , D ₃	D ₂	D ₃	
...	
1/2 N+19	D _{N-6} , D _{N-5}	D _{N-6}	D _{N-5}	
1/2 N+20	D _{N-4} , D _{N-3}	D _{N-4}	D _{N-3}	
1/2 N+21	D _{N-2} , D _{N-1}	D _{N-2}	D _{N-1}	

16.2.3 Symbol structure

In the BPM-BPSK modulation scheme, each symbol is capable of carrying two bits of information: one bit is used to determine the position of a burst of pulses, while an additional bit is used to modulate the phase (polarity) of this same burst.

The structure and timing of a symbol is illustrated in Figure 16-4. Each symbol shall consist of an integer number of possible chip positions, N_{cpb} , each with duration T_c . The overall symbol period denoted by T_{dsym} is given by $T_{dsym} = N_c T_c$. Furthermore, each symbol is divided into two BPM intervals each with duration $T_{BPM} = T_{dsym}/2$, which enables binary position modulation.

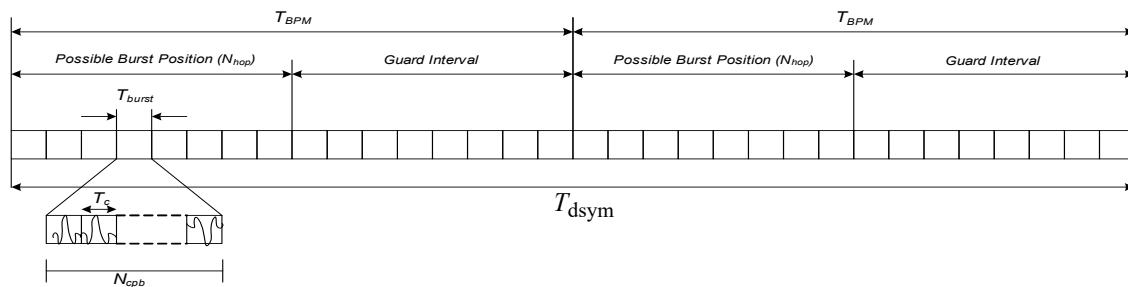


Figure 16-4—HRP UWB PHY symbol structure

A burst is formed by grouping N_{cpb} consecutive chips and has duration $T_{\text{burst}} = N_{\text{cpb}}T_c$. The location of the burst in either the first half or the second half of the symbol indicates one bit of information. Additionally, the phase of the burst (either -1 or $+1$) is used to indicate a second bit of information.

In each symbol interval, a single burst event shall be transmitted. The fact that burst duration is typically much shorter than the BPM duration, i.e., $T_{\text{burst}} \ll T_{\text{BPM}}$, provides for some multi-user access interference rejection in the form of time hopping. The total number of burst durations per symbol, N_{burst} , is given by $N_{\text{burst}} = T_{\text{dsym}} / T_{\text{burst}}$. In order to limit the amount of intersymbol interference caused by multipath, only the first half of each T_{BPM} period shall contain a burst. Therefore, only the first $N_{\text{hop}} = N_{\text{burst}}/4$ possible burst positions are candidate hopping burst positions within each BPM interval. Each burst position can be varied on a symbol-to-symbol basis according to a time hopping code as described in 16.3.

16.2.4 PSDU timing parameters

The PSDU rate-dependent parameters and timing-related parameters are summarized in Table 16-4. Within each HRP UWB channel {0:15}, the peak PRF shall be 499.2 MHz. This rate corresponds to the highest frequency at which a compliant transmitter shall emit pulses. Additionally, the mean PRF is defined as the total number of pulses emitted during a symbol period divided by the length of the symbol period.

There are two possible preamble code lengths (31 or 127) and three possible mean PRFs (15.6 MHz, 3.90 MHz, and 62.4 MHz). A compliant device shall implement support for the preamble code length of 31 and shall also support both the 15.6 MHz and 3.90 MHz mean PRFs for the PSDU as depicted in Table 16-4. The use of the length 127 code is optional; when implemented, the mean PRF of the PSDU shall be 62.4 MHz.

Channels {4, 7, 11, 15} are all optional channels and are differentiated from other channels by the larger bandwidth (>500 MHz) of the transmitted signals. These channels overlap the existing lower bandwidth channels. The larger bandwidth enables devices operating in these channels to transmit at a higher power (for fixed power spectral density (PSD) constraints), and thus they may achieve a longer communication range. The larger bandwidth pulses offer enhanced multipath resistance. Additionally, larger bandwidth leads to more accurate range estimates. The admissible data rates, preamble code lengths, PRFs, and modulation timing parameters are listed in Table 16-4.

Each channel allows for several data rates that are obtained by modifying the number of chips within a burst, while the total number of possible burst positions remains constant. Therefore, the symbol period, T_{dsym} , changes to obtain the stated symbol rate and bit rates.

Each row in Table 16-4 completely describes all timing parameters shown in Figure 16-4 for each permitted combination of channel number, preamble code length, and PRF.

The channel number parameter column identifies the HRP UWB PHY channel numbers where the remaining PSDU timing parameters in the current row are valid. Association between channel number and center frequency is given in Table 16-27.

The peak PRF states the highest frequency in megahertz at which a compliant transmitter shall emit pulses. The peak PRF is also used to derive the chip duration T_c by the formula $T_c = 1/(\text{peakPRF})$. The value of T_c is approximately 2 ns.

The bandwidth denotes the 3 dB bandwidth of the HRP UWB pulses.

NOTE—The bandwidth is not necessarily the inverse of the chip duration T_c .

Pulse shape and bandwidth are further defined in 16.4.4.

Table 16-4—HRP UWB PHY rate-dependent and timing-related parameters

Channel Number	Peak PRF MHz	Bandwidth MHz	Preamble Code Length	Viterbi Rate	Modulation & Coding			Data Symbol Structure				Data				
					Overall FEC Rate	#Burst Positions per Symbol N_{burst}	#Hop Bursts N_{hop}	#Chips Per Symbol N_{chp}	Burst Duration T_{burst} (ns)	Symbol Duration T_{sym} (ns)	Symbol Rate (MHz)	Bit Rate Mb/s	Mean PRF (MHz)			
{9,3,5,6, 8;10,12;14}	499.2	499.2	31	0.5	0.87	0.44	32	8	128	4096	256.41	8205.13	0.12	0.11	15.60	
	499.2	499.2	31	0.5	0.87	0.44	32	8	16	512	32.05	1025.64	0.98	0.85	15.60	
	499.2	499.2	31	0.5	0.87	0.44	32	8	2	64	4.01	128.21	7.80	6.81	15.60	
	499.2	499.2	31	1	0.87	0.87	32	8	1	32	2.00	64.10	15.60	27.24	15.60	
{0,3,5,6, 8;10,12;14}	499.2	499.2	31	0.5	0.87	0.44	128	32	32	4096	64.10	8205.13	0.12	0.11	3.90	
	499.2	499.2	31	0.5	0.87	0.44	128	32	4	512	8.01	1025.64	0.98	0.85	3.90	
	499.2	499.2	31	0.5	0.87	0.44	128	32	2	256	4.01	512.82	1.95	1.70	3.90	
	499.2	499.2	31	1	0.87	0.87	128	32	1	128	2.00	256.41	3.90	6.81	3.90	
{0,3,5,6, 8;10,12;14}	499.2	499.2	127	0.5	0.87	0.44	8	2	512	4096	1025.64	8205.13	0.12	0.11	62.40	
	499.2	499.2	127	0.5	0.87	0.44	8	2	64	512	128.21	1025.64	0.98	0.85	62.40	
	499.2	499.2	127	0.5	0.87	0.44	8	2	8	64	16.03	128.21	7.80	6.81	62.40	
	499.2	499.2	127	0.5	0.87	0.44	8	2	2	16	4.01	32.05	31.20	27.24	62.40	
{4,11}	499.2	1331.2	31	0.5	0.87	0.44	32	8	128	4096	256.41	8205.13	0.12	0.11	15.60	
	499.2	1331.2	31	0.5	0.87	0.44	32	8	16	512	32.05	1025.64	0.98	0.85	15.60	
	499.2	1331.2	31	0.5	0.87	0.44	32	8	2	64	4.01	128.21	7.80	6.81	15.60	
	499.2	1331.2	31	1	0.87	0.87	32	8	1	32	2.00	64.10	15.60	27.24	15.60	
{4,11}	499.2	1331.2	127	0.5	0.87	0.44	8	2	512	4096	1025.64	8205.13	0.12	0.11	62.40	
	499.2	1331.2	127	0.5	0.87	0.44	8	2	64	512	128.21	1025.64	0.98	0.85	62.40	
	499.2	1331.2	127	0.5	0.87	0.44	8	2	8	64	16.03	128.21	7.80	6.81	62.40	
	499.2	1331.2	127	0.5	0.87	0.44	8	2	2	16	4.01	32.05	31.20	27.24	62.40	
7	499.2	1081.6	31	0.5	0.87	0.44	32	8	128	4096	256.41	8205.13	0.12	0.11	15.60	
	499.2	1081.6	31	0.5	0.87	0.44	32	8	16	512	32.05	1025.64	0.98	0.85	15.60	
	499.2	1081.6	31	1	0.87	0.87	32	8	1	32	2.00	64.10	15.60	27.24	15.60	
	499.2	1081.6	127	0.5	0.87	0.44	8	2	512	4096	1025.64	8205.13	0.12	0.11	62.40	
7	499.2	1081.6	127	0.5	0.87	0.44	8	2	64	512	128.21	1025.64	0.98	0.85	62.40	
	499.2	1081.6	127	0.5	0.87	0.44	8	2	8	64	16.03	128.21	7.80	6.81	62.40	
	499.2	1081.6	127	0.5	0.87	0.44	8	2	2	16	4.01	32.05	31.20	27.24	62.40	
	499.2	1081.6	127	0.5	0.87	0.44	8	2	1	32	2.00	64.10	15.60	27.24	15.60	
15	499.2	1354.97	31	0.5	0.87	0.44	32	8	128	4096	256.41	8205.13	0.12	0.11	15.60	
	499.2	1354.97	31	0.5	0.87	0.44	32	8	16	512	32.05	1025.64	0.98	0.85	15.60	
	499.2	1354.97	31	0.5	0.87	0.44	32	8	2	64	4.01	128.21	1025.64	0.98	0.85	15.60
	499.2	1354.97	31	1	0.87	0.87	32	8	1	32	2.00	64.10	15.60	27.24	15.60	
15	499.2	1354.97	127	0.5	0.87	0.44	8	2	512	4096	1025.64	8205.13	0.12	0.11	62.40	
	499.2	1354.97	127	0.5	0.87	0.44	8	2	64	512	128.21	1025.64	0.98	0.85	62.40	
	499.2	1354.97	127	0.5	0.87	0.44	8	2	8	64	16.03	128.21	7.80	6.81	62.40	
	499.2	1354.97	127	0.5	0.87	0.44	8	2	2	16	4.01	32.05	31.20	27.24	62.40	

The preamble code length parameter denotes the length of the preamble code to be used during the SHR portion of a PPDU. Individual codes to be used on each channel are given in Table 16-7 (length 31) and Table 16-8 (length 127).

This Viterbi rate parameter determines the rate of the convolutional code applied to the PHY Payload bits. A value of 1 indicates that no convolutional coding is applied, while a value of 0.5 indicates that a rate 1/2 code as described in 16.3.3.3 is applied.

The RS rate parameter indicates the (63,55) Reed-Solomon code rate, which is approximately 0.87. The Reed-Solomon code is applied to the entire PSDU. Reed-Solomon encoding is further described in 16.3.3.2.

The overall FEC rate is determined by the product of the Viterbi rate and the Reed-Solomon rate and has either a value of 0.44 or 0.87.

The burst positions per symbol parameter is the total number of possible burst positions in a data symbol period. N_{burst} has been chosen so that for each mean PRF a data symbol consists of a fixed number of burst durations.

The hop bursts parameter is the number of burst positions that may contain an active burst, that is, a burst containing HRP UWB pulses. The value is computed as $N_{\text{hop}} = N_{\text{burst}}/4$.

The chips per burst parameter is the number of chip T_c durations within each burst period T_{burst} . Each burst consists of a multiple number of consecutive chips, as illustrated in Figure 16-4. Depending on the data rate to be used in the transmission of the PSDU, the number of chips in a burst varies, e.g., for low data rates, the burst consists of more chip periods than for high data rates. Particular, values of N_{cpb} have been selected so that the following is a valid data rate: $(2 \times \text{Overall FEC Rate})/(N_{\text{cpb}} \times N_{\text{burst}} \times T_c)$.

The burst duration parameter is simply the duration of a burst and is computed as $T_{\text{burst}} = N_{\text{cpb}} \times T_c$.

The symbol period parameter is the duration of a modulated and coded PSDU symbol on the air and is computed as follows: $T_{\text{dsym}} = N_{\text{burst}} \times T_{\text{burst}}$.

The symbol rate parameter is the inverse of the PSDU symbol period $1/T_{\text{dsym}}$.

The bit rate parameter is the user information rate considering FEC and is computed as follows:

$$\text{Bit Rate} = 2 \times (\text{Overall FEC Rate})/T_{\text{dsym}}$$

The mean PRF parameter is the average PRF during the PSDU portion of a PHY frame and is computed as follows:

$$\text{Mean PRF} = N_{\text{cpb}}/T_{\text{dsym}}$$

16.2.5 Preamble timing parameters

Due to the variability in the preamble code length and the PRF, there are several admissible values for the timing parameters of a preamble symbol. These values are summarized in Table 16-5. In this subclause, a preamble symbol is defined as the waveform consisting of one whole repetition of the modulated preamble code (either length 31 or 127). Details on the construction of the preamble symbol for various code lengths and PRFs are given in 16.2.6. For each target PRF, the preamble is constructed from a preamble code, C_i , by inserting a number of chip durations between code symbols. The number of chip durations to insert is denoted by δ_L , values for each code length and PRF are given in Table 16-5, and the chip insertion is detailed in 16.2.6.2.

Table 16-5—Preamble parameters

Channel number	C_i Code length	Peak PRF (MHz)	Mean PRF (MHz)	Delta length δ_L	#Chips per symbol	Symbol duration T_{psym} (ns)	Base rate Msymbol/s
{0:15}	31	31.20	16.10	16	496	993.59	1.01
{0:3, 5:6, 8:10, 12:14}	31	7.80	4.03	64	1984	3974.36	0.25
{0:15}	127	124.80	62.89	4	508	1017.63	0.98

Table 16-5 presents the timing parameters during the SHR field portion of an HRP UWB PPDU, while Table 16-4 presents the timing parameters for the PSDU portion of the frame. First, note that the preamble is sent at a slightly higher mean PRF than the data, as defined in Table 16-4. This is due to the fact that length 31 or 127 ternary codes are being used within the SHR, and the number of chips within the SHR is no longer a power of 2. For example, for the two mandatory PRFs in channels {0:3, 5:6, 8:10, 12:14}, the peak PRFs during the preamble are 31.2 MHz and 7.8 MHz, respectively, and the corresponding mean PRFs during the preamble are 16.10 MHz and 4.03 MHz, respectively. The corresponding mean PRFs during the PSDU are 15.60 MHz and 3.90 MHz, respectively. The remaining peak and mean PRF values for other optional HRP UWB channels and the optional length 127 code are listed in Table 16-5.

The base symbol rate is defined as the rate at which the preamble symbols are sent. The base rates corresponding to the two mandatory mean PRFs of 16.10 MHz and 4.03 MHz are 1 Msymbol/s and 0.25 Msymbol/s, respectively, and are listed in the column with the heading “Base rate” in Table 16-5. These symbol rates correspond to a preamble symbol period of 993.59 ns and 3974.36 ns for the two mandatory PRFs.

Finally, for each HRP UWB PPDU, there are four possible durations of the SHR. This is due to the four possible lengths of SYNC field in the SHR, as described in 16.2.6. The SYNC field consists of repetitions of the preamble symbol. The number of preamble symbol repetitions are 16, 64, 1024, and 4096. These different SYNC field lengths yield different time durations of the PPDU. The relationship between SYNC field length and frame duration is shown in Table 16-6. For each channel, the number of chips in an individual preamble symbol is shown in the row titled “ N_c ”. N_c is a function of the PRF used within the channel and, therefore, has either two or three values. For each value of N_c , the admissible preamble symbol periods are defined, and the duration of the SYNC portion of the SHR for each length (16, 64, 1024, or 4096) is denoted as T_{sync} . The values of the frame duration parameters are shown in Table 16-6 for each of the channels.

Table 16-6—HRP UWB PHY frame-dependent parameters

Parameter	Description		Value		
Channel	HRP UWB PHY channel number		{0:15}		{0:3, 5:6, 8:10, 12:14}
PRF _{mean}	Mean PRF (MHz)		16.10	62.89	4.03
N_c	Number of chips per preamble symbol		496	508	1984
T_{psym}	Preamble symbol period (ns)		993.6	1017.6	3974.4

Table 16-6—HRP UWB PHY frame-dependent parameters (continued)

Parameter	Description		Value	
N_{sync}	Number of symbols in the packet sync sequence	Short	16	
		Default	64	
		Medium	1024	
		Long	4096	
T_{sync}	Duration of the packet sync sequence (μ s)	Short	15.9	16.3
		Default	63.6	65.1
		Medium	1017.4	1042.1
		Long	4069.7	4168.2
N_{sfd}	Number of symbols in the SFD		8 or 64	
T_{sfd}	Duration of the SFD (μ s)		7.9 or 63.6	8.1 or 65.1
N_{pre}	Number of symbols in the SHR	Short	24 or 80	
		Default	72 or 128	
		Medium	1032 or 1088	
		Long	4104 or 4160	
T_{pre}	Duration of the SHR preamble (μ s)	Short	23.8 or 79.5	24.4 or 270.6
		Default	71.5 or 127.2	73.3 or 319.5
		Medium	1025.4 or 081.0	1050.2 or 1296.4
		Long	4077.7 or 4133.3	4176.3 or 4422.6
N_{CCA_PHR}	Number of multiplexed preamble symbols in PHR		4 or 32	
N_{CCA_data}	Number of multiplexed preamble symbols in the PHY Payload field		$T_{pre}/(4 \times T_{dsym/M})$	

^a The use of the long SYNC sequence is not allowed when operating at a mean PRF of 4.03 MHz.

16.2.6 SHR field

16.2.6.1 Overview

Four mandatory preambles are defined: a default preamble, a short preamble, a medium preamble, and a long preamble. The preamble to be used in the transmission of the current frame is determined by the value of the UwbPreambleSymbolRepetitions parameter in the MCPS-DATA.request primitive.

The SHR field shall be formatted as illustrated in Figure 16-5.

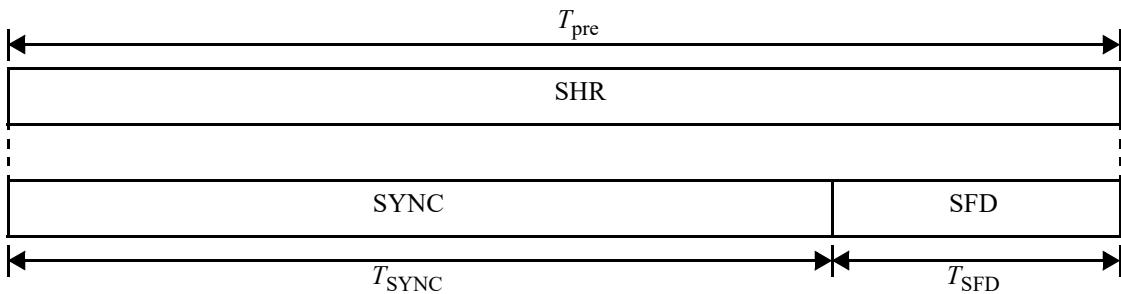


Figure 16-5—SHR field structure

16.2.6.2 SYNC field

Each PAN operating on one of the HRP UWB PHY channels is also identified by a preamble code. The preamble code is used to construct symbols that constitute the SYNC field as shown in Figure 16-5. The HRP UWB PHY supports two lengths of preamble code: a length 31 code and an optional length 127 code. Each preamble code is a sequence of code symbols drawn from a ternary alphabet $\{-1, 0, 1\}$ and selected for use in the HRP UWB PHY because of their periodic autocorrelation properties. The length 31 code sequences are shown in Table 16-7, while the length 127 code sequences are shown in Table 16-8. The codes that may be used in each of the HRP UWB PHY channels is restricted, and the particular code assignments are made in Table 16-7 and Table 16-8. Specifically, the last column in each table indicates the set of HRP UWB channel numbers that permit use of the code. Additionally, 8 of the length 127 codes are reserved for use with the private ranging protocol only and are not used during normal WPAN operation. This restriction is indicated in the third column of Table 16-8 as well.

Table 16-7—Length 31 ternary codes

Code index	Code sequence	Channel number ^a
1	- 0 0 0 0 + 0 - 0 + + + 0 + - 0 0 0 + - + + + 0 0 - + 0 - 0	0, 1, 8, 12
2	0 + 0 + - 0 + 0 + 0 0 0 - + + 0 - + - - 0 0 + 0 0 + + 0 0 0	0, 1, 8, 12
3	- + 0 + + 0 0 0 - + - + + 0 0 + + 0 + 0 0 - 0 0 0 0 - 0 + 0 -	2, 5, 9, 13
4	0 0 0 0 + - 0 0 - 0 0 - + + + 0 + - + 0 0 0 + 0 - 0 + + 0 -	2, 5, 9, 13
5	- 0 + - 0 0 + + + - + 0 0 0 - + 0 + + + 0 - 0 + 0 0 0 0 - 0 0	3, 6, 10, 14
6	+ + 0 0 + 0 0 - - - + - 0 + + - 0 0 0 + 0 + 0 - + 0 + 0 0 0 0	3, 6, 10, 14
7	+ 0 0 0 0 + - 0 + 0 + 0 0 + 0 0 0 + 0 + - - - 0 - + 0 0 - +	4, 7, 11, 15
8	0 + 0 0 - 0 - 0 + + 0 0 0 0 - - + 0 0 - + 0 + + - + + 0 + 0 0	4, 7, 11, 15

^aNote that codes indexed 1 through 6 may also be used for HRP UWB channels 4, 7, 11, and 15 (i.e., channels whose bandwidth is wider than 500 MHz) if interchannel communication is desired.

The assignment of preamble codes to channels has been done to enable interchannel communication. In other words, it is possible that a device operating on a wideband channel $\{4, 7, 11, 15\}$ may communicate with a device on a channel with which it overlaps.

Table 16-8—Optional length 127 ternary codes

Table 16-8—Optional length 127 ternary codes (*continued*)

Code index	Code sequence	Channel number ^a
23	0 0 0 + + 0 + 0 - + - 0 - 0 0 - 0 + 0 + 0 + + 0 + - - 0 0 + 0 0 0 0 - 0 0 0 + 0 0 + 0 0 - + + 0 - 0 + 0 0 0 0 0 + 0 + + - + 0 0 + + - 0 + - + + + - 0 - - 0 0 - 0 - - 0 0 0 + - 0 0 + - 0 - + 0 + 0 0 0 + + - - 0 0 0 0 + + - 0 0 0 - 0 + 0 0 - + 0 0 0	0-15; DPS only
24	+ 0 + - 0 - 0 0 0 + + - + 0 0 0 0 0 + 0 0 - - 0 + - 0 0 0 0 - 0 - 0 0 0 0 0 0 + - - 0 - + 0 + - - + 0 + - - - + 0 + 0 0 + 0 + 0 - - + 0 - 0 + 0 + 0 + 0 + + + 0 0 0 + + 0 0 + 0 - + 0 0 - - 0 0 0 - 0 + + - + 0 - - + 0 0 + 0 0 0 + 0 0 0 0 + + 0	0-15; DPS only

^a Note that codes indexed 9 through 12 may also be used for HRP UWB channels 4, 7, 11, and 15 (i.e., channels whose bandwidth is wider than 500 MHz) if interchannel communication is desired.

^b Note that for spectral efficiency reasons the use of preamble code index 10 is not recommended for packets with the PHR at a lower symbol rate than that of the payload.

For a WPAN using the ternary code indexed by i , the SYNC field shall consist of N_{sync} repetitions of the symbol S_i , where S_i is the code C_i spread by the delta function δ_L of length L as shown in Table 16-5. The spreading operation, where code C_i is extended to the preamble symbol period indicated in Table 16-5, is described mathematically as follows:

$$S_i = C_i \otimes \delta_L(n)$$

$$\delta_L(n) = \begin{cases} 1 & n = 0 \\ 0 & n = 1, 2, \dots, L-1 \end{cases}$$

where the operator \otimes indicates a Kronecker product. After the Kronecker operation, a preamble symbol is formed as depicted in Figure 16-6, where $L-1$ zeros have been inserted between each ternary element of C_i .

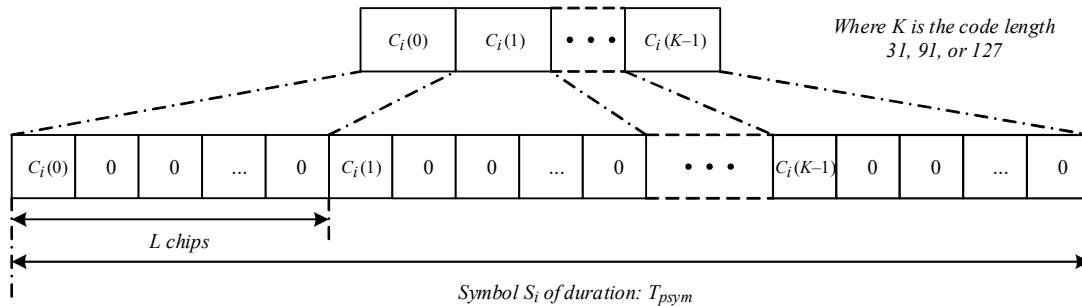


Figure 16-6—Construction of symbol S_i from code C_i

The spreading factor L , number of chips per symbol, preamble symbol period T_{psym} , and base symbol rate for different channels are given in Table 16-5.

The HRP-ERDEV shall support the (HPRF mode) length 91 codes specified in Table 16-9 with the parameters specified in Table 16-10. The *phyCurrentCode* attribute specifies the code to be used. The selected code sequence C_i is spread to generate the preamble symbol S_i using the delta function δ_L and length L given in Table 16-10.

Table 16-9—Length 91 ternary codes for the HRP-ERDEV in HPRF mode

NOTE—Among these codes, the pairs of codes selected by code indices {25 and 26}, {27 and 28}, or {29 and 30} have the lowest cross-correlation value between the codes of the pair, as per Verso and Niewczas [B35], and therefore would be the preferential choice to use where there are two independent networks co-existing, i.e., choosing one code from the pair for each network.

Table 16-10—Preamble parameters for HRP-ERDEV length 91 codes

C_i code length	Peak PRF (MHz)	Mean PRF (MHz)	Delta length δ_L	#Chips per symbol	Symbol duration T_{psym} (ns)	Base rate Msymbol/s
91	124.8	111.09	4	364	729.17	1.37

The length of the SYNC field scales with the number of PSR, that is the N_{sync} repetitions of S_i . In HPRF mode, the HRP-ERDEV shall support transmission and reception with PSR values of 32 and 64, with optional PSR values being 16, 24, 48, 96, 128, and 256. The HRP-ERDEV's SYNC field length is specified by the *phyHrpUwbPsr* attribute, when this is zero the UwbPreambleSymbolRepetitions parameter of the MCPS-DATA.request determines the transmitted SYNC field length.

16.2.6.3 SFD field

The short SFD is used for the default and medium data rates while the long SFD is used for the optional low data rate of 110 kb/s, as shown in Figure 16-5. The short SFD shall be $[0 +1 0 -1 +1 0 0 -1]$ spread by the preamble symbol S_i , where the leftmost bit shall be transmitted first in time. The long SFD shall be obtained by spreading the sequence $[0 +1 0 -1 +1 0 0 -1 0 +1 0 -1 +1 0 0 -1 -1 0 0 +1 0 -1 0 +1 0 +1 0 0 0 -1 0 -1 0 -1 0 0 +1 0 -1 -1 0 -1 +1 0 0 0 0 +1 +1 0 0 -1 -1 -1 +1 +1 +1 0 0 0 0 +1 +1]$ by the preamble symbol S_i . The structure of the SHR and the two possible SFDs are shown in Figure 16-5.

In the BPRF mode, the HRP-ERDEV shall support the length 8 SFD specified in Table 16-11 (i.e., for the *phyHrpUwbSfdSelector* value of 2) and shall also support the short SFD given in the paragraph above.

Table 16-11—SFD sequences for the HRP-ERDEV

SFD #, value of the <i>phyHrpUwbSfdSelector</i> attribute	Selected SFD length	Selected SFD sequence	HRP-ERDEV support
0	8	The HRP-ERDEV shall use the short SFD defined previously	Mandatory
1	4	[-1 -1 +1 -1]	Mandatory
2	8	[-1 -1 -1 +1 -1 -1 +1 -1]	Mandatory
3	16	[-1 -1 -1 -1 +1 +1 -1 -1 +1 -1 +1 -1 -1 +1 -1]	Mandatory
4	32	[-1 -1 -1 -1 -1 -1 +1 -1 -1 +1 -1 +1 -1 -1 +1 -1 +1 -1 -1 +1 +1 -1 -1]	Optional

In the HPRF mode, the HRP-ERDEV shall support the length 4, 8, and 16 SFD specified in Table 16-11 for the *phyHrpUwbSfdSelector* values of 1, 2, and 3. Support of the length 32 SFD specified in Table 16-11 is optional.

In each case the SFD specified in Table 16-11 is spread by the preamble symbol S_i , where the leftmost bit of the SFD shall be transmitted first in time.

16.2.7 PHR field

16.2.7.1 General

A PHR field shall be formatted as illustrated in Figure 16-7.

Bits: 0–1	2–8	9	10	11–12	13–18
Data Rate	Frame Length	Ranging	Reserved	Preamble Duration	SECDED

Figure 16-7—PHR field format

The Data Rate field indicates the data rate of the PHY Payload field. A list of the data rates supported in the operating channel is in the *phyHrpUwbDataRatesSupported* attribute. The bits shall be set, depending on the mean PRF, according to Table 16-12. Support for the 850 kb/s data rate is mandatory; all others are optional.

Table 16-12—Nominal data rates

DataRate parameter value	b0 b1	Nominal data rate (Mb/s) for 15.60 MHz and 62.40 MHz mean PRF	Nominal data rate (Mb/s) for 3.90 MHz mean PRF
1	00	0.11	0.11
2	01	0.85	0.85
3	10	6.81	1.70
4	11	27.24	6.81

NOTE—The DataRate parameter value is the DataRate parameter used in MCPS-DATA primitives.

The Frame Length field shall be an unsigned integer number that indicates the number of octets in the PSDU field. The Frame Length field shall be passed to the reference modulator most significant bit first.

The Ranging field shall be set to one if the current frame is an RFRAIME and shall be set to zero otherwise.

The Preamble Duration field represents the length (in preamble symbols) of the SYNC portion of the SHR field. The Preamble Duration field shall be set according to Table 16-13.

Table 16-13—Preamble Duration field values

Field value, b11 b12	SYNC length (symbols)
00	16
01	64
10	1024
11	4096

The Preamble Duration field is intended for use during ranging operations and is used by a receiver of the PPDU to help determine at which preamble symbol the PHY acquired and began tracking the preamble. A receiver may use the Preamble Duration field to set the value of its own preamble duration based upon the received value when communicating a ranging Ack frame.

The SECDED (single error correct, double error detect) field is a simple Hamming block code that enables the correction of a single error and the detection of two errors at the receiver. The SECDED bit values, b13, ..., b18 depend on PHR bits, b0, ..., b12 and are computed as follows:

$$b_{18} = \text{XOR}(b_1, b_0, b_8, b_6, b_4, b_3, b_{10}, b_{11})$$

$$b_{17} = \text{XOR}(b_0, b_6, b_5, b_3, b_2, b_9, b_{10}, b_{12})$$

$$b_{16} = \text{XOR}(b_1, b_8, b_7, b_3, b_2, b_9, b_{10})$$

$$b_{15} = \text{XOR}(b_8, b_7, b_6, b_5, b_4, b_9, b_{10})$$

$$b_{14} = \text{XOR}(b_{12}, b_{11})$$

$$b_{13} = \text{XOR}(b_0, b_1, b_2, b_3, b_4, b_5, b_6, b_7, b_8, b_9, b_{10}, b_{11}, b_{12}, b_{14}, b_{15}, b_{16}, b_{17}, b_{18})$$

16.2.7.2 PHR field for HRP-ERDEV in BPRF mode

In the BPRF mode, the HRP-ERDEV shall use the PHR as specified in 16.2.7.1. Optionally, this PHR may be sent at the same symbol rate as the data. This is determined by setting of the *phyHrpUwbPhrDataRate* attribute, as per Table 16-14.

Table 16-14—PHR and PSDU bit rates for the HRP-ERDEV in BPRF mode

Value of the <i>phyHrpUwbPhrDataRate</i> attribute	PHR bit rate	PSDU bit rate
DRBM_LP	975 kb/s (850 kb/s nominal)	6.8 Mb/s
DRBM_HP	7.8 Mb/s (6.8 Mb/s nominal)	6.8 Mb/s

16.2.7.3 PHR field for HRP-ERDEV in HPRF mode

In the HPRF mode, the HRP-ERDEV shall use the PHR format as shown in Figure 16-8. This is transmitted without Reed-Solomon coding. Both PSDU and PHR shall use the same convolutional code and modulation as described in 16.3.4.

Bits: 0	1	2–11	12	13–18
A1	A0	PHY payload length	Ranging	SECDED

Figure 16-8—HRP-ERDEV HPRF mode PHY header

This PHR includes the Ranging and SECDED fields encoded as specified in 16.2.7.1, a 10-bit PHY payload length field, and two additional functionality PHR bits A0 and A1, which shall be zero when not being used. The PHY payload length field shall be passed to the modulator most significant bit first.

For the mandatory convolutional encoding, in the case of a zero-length data field, the full 21 symbols of the PHR shall be transmitted, with the leading data bits D0 and D1 set to zero to correctly form the tail, as specified in Table 16-2.

In the optional PPDU format where the STS follows the payload, as selected by STS packet configuration value of 2 (in Table 16-1), the additional functionality PHR bits A1 and A0 may be optionally used to signal an additional gap between the payload and the STS. Where this feature is being employed, the receiver shall interpret A1 and A0 to select the gap as specified by the PIB attributes listed in Table 16-15. It is the responsibility of the higher layers to correctly set the *phyHrpUwbPhrA0* and *phyHrpUwbPhrA1* attributes so that A1 and A0 are correctly set in the PHR, and that the appropriate *phyHrpUwbStsPC2TxGap* is set to correctly align with the remote receiver's configuration of the attributes in Table 16-15.

Table 16-15—Optional payload to STS gap

A1	A0	Gap (chips)
0	0	<i>phyHrpUwbStsPC2RxGap0</i>
0	1	<i>phyHrpUwbStsPC2RxGap1</i>
1	0	<i>phyHrpUwbStsPC2RxGap2</i>
1	1	<i>phyHrpUwbStsPC2RxGap3</i>

The A1 and A0 fields of the PHR may optionally be used to extend the PHY payload length field, under control of the *phyHrpUwbPsduSize* attribute, as specified in Table 16-16. Since the PSDU length is determined by the MCPS-DATA.request primitive, the *phyHrpUwbPhrA0* and *phyHrpUwbPhrA1* attributes are used/ignored as specified in Table 16-16.

Table 16-16—HPR-ERDEV maximum PSDU length extension

Value of the <i>phyHrpUwbPsduSize</i> attribute	Maximum PSDU length (octets)	Description
0	1023	Neither A1 nor A0 are treated as part of the PHY payload length field, and the PSDU is limited to 1023 octets by the 10-bit PHY payload length field.
1	2047	A0 is treated as the most significant bit of the PHY payload length field. The PSDU length is thus specified by an 11-bit field giving a 2047-octet maximum length, and the <i>phyHrpUwbPhrA0</i> attribute is ignored.
2	4095	A1 and A0 are treated as the most and second-most significant bits of the PHY payload length field, respectively. The PSDU length is thus specified by a 12-bit field giving a 4095-octet maximum length, and both <i>phyHrpUwbPhrA0</i> and <i>phyHrpUwbPhrA1</i> attributes are ignored.

16.2.8 PHY Payload field

The PHY Payload field is encoded as shown in Figure 16-9.

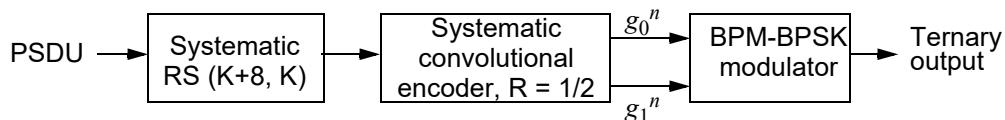


Figure 16-9—PHY Payload field encoding process

The PHY Payload field shall be formed as follows:

- Encode the PSDU using systematic Reed-Solomon block code, which adds 48 parity bits as described in 16.3.3.2.
- Encode the output of the Reed-Solomon block code using a systematic convolutional encoder as described in 16.3.3.3, except in the cases where the Viterbi rate for the modulation is one, as defined in Table 16-4. In these cases, the convolutional encoder is bypassed.

- For the HRP-ERDEV in its HPRF mode, spread and modulate the encoded block as described in 16.3.4, otherwise spread and modulate the encoded block using BPM-BPSK modulation as described in 16.3.

16.2.9 Scrambled timestamp sequence (STS) field

16.2.9.1 General

The STS consists of a sequence of pseudo-randomized pulses generated, as specified below, using a DRBG based on AES-128 in counter mode. These pulse sequences are arranged in (one to four) blocks of active segments encapsulated by silent intervals, called “gaps”. The duration of these gaps shall be 512 chips ($\sim 1 \mu\text{s}$). Figure 16-10 shows the extent of the STS when consisting of one or two segments. Table 16-17 specifies the numbers of segments and the segment lengths that shall be supported.

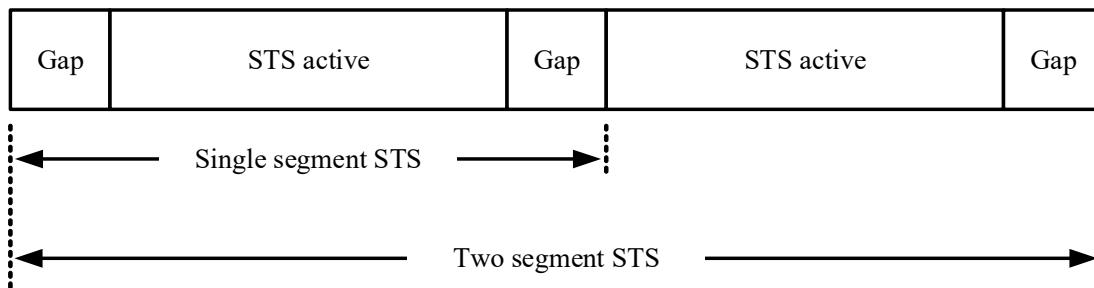


Figure 16-10—STS segments

In the optional PPDU format where the STS follows the payload, (i.e., STS packet configuration value of 2 in Table 16-1), an optional additional gap as specified by the *phyHrpUwbStsPC2TxGap* attribute shall be inserted between the PSDU and the STS.

16.2.9.2 The STS generation DRBG

The STS shall be generated using a DRBG with the structure shown in Figure 16-11. This is using advanced encryption standard (AES) in counter mode. Each time the DRBG is run, it produces a 128-bit pseudo-random number used to form 128 pulses of the STS, as specified in 16.2.9.3. Higher layers should add pre-processing and/or re-seeding if specific levels of backtracking resistance are required and/or a very large number of iterations is performed.

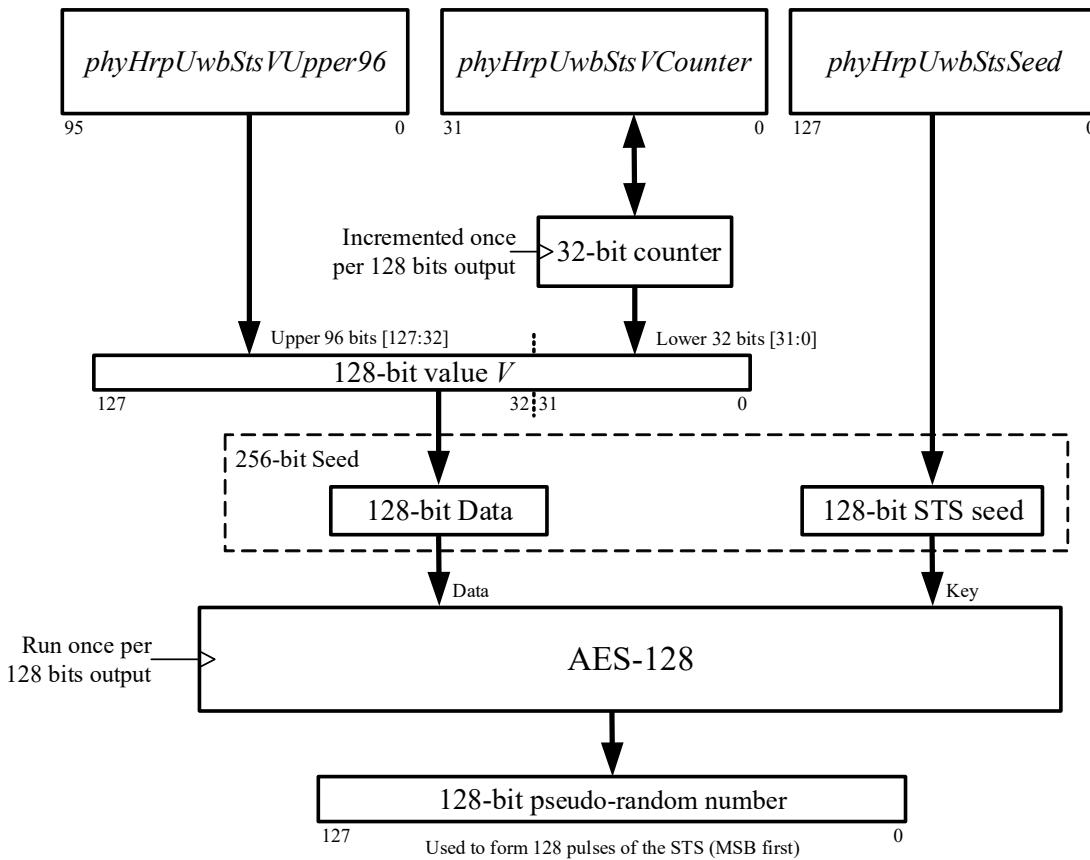


Figure 16-11—DRBG for STS

The higher layer is responsible for setting the 128-bit STS seed, via the *phyHrpUwbStsSeed* attribute, along with the 128-bit initial value for *V*, via the *phyHrpUwbStsVCounter* and *phyHrpUwbStsVUpper96* attributes. The 32-bit counter part of *V* is incremented after each iteration of the DRBG to give a new *V* value each time it is run to produce 128 bits/pulses for the STS.

A conforming implementation can be verified using the test vector given in Annex G.

While this specification covers the transmitter operation, it is expected that the receiver will use the same mechanism and aligned values of the STS seed and *V* to generate a complementary sequence for cross correlation with the transmitted sequence. The mechanisms for agreeing, coordinating, and synchronizing these values between HRP-ERDEV are the responsibility of the higher layers. The RSSD IE described in 10.29.8.2 may be used to synchronize the values of *V* and the STS seed between HRP-ERDEVs before they participate in a ranging exchange employing the STS.

16.2.9.3 Forming the STS

Each iteration of the DRBG specified in 16.2.9.2 produces a 128-bit pseudo-random number. This is taken and transmitted most significant bit first, where each bit of value zero produces a positive polarity pulse and each bit of value one produces a negative polarity pulse. These are spread as described in 16.2.6.2 by the delta function δ_L of length $L = 8$ in the BPRF mode, and of length $L = 4$ in the HPRF mode. The resultant PRF for these modes is specified in Table 16-17 along with the number of segments and the segment lengths that shall be supported. Figure 16-10 shows the structure of the STS in terms of segments. Where the STS

consists of more than one active segment, each active segment shall be the same length. Table 16-18 and Table 16-19 define the configuration options for segment length and number of segments in the STS.

Table 16-17—STS parameters

HRP-ERDEV mode	Delta Length δ_L	Pulse spacing (chips)	PRF (MHz)	Length of active segment in units of 512 chips (~1 µs)	Number of segments supported
BPRF mode	8	8	62.4	64 mandatory	1 mandatory
HPRF mode	4	4	124.8	32, 64, 128 mandatory 16, 256 optional	1, 2 mandatory 3, 4 optional

Table 16-18—STS segment length configuration

Value of segment length specifier (see Note 1)	Selected length of active STS segment in units of 512 chips (~1 µs)
0	16
1	32
2	64
3	128
4	256

NOTE 1—The segment length specifier value in Table 16-18 applies to the TxStsSegmentLength and RxStsSegmentLength parameters of the MLME-STS.request primitive specified in 10.29.9.4.1 and to the *phyHrpUwbStsTxSegLen* and *phyHrpUwbStsRxSegLen* attributes.

Table 16-19—STS number of segments configuration

Value of number of segments specifier (see Note 2)	Selected number of STS segments transmitted or expected in the receiver
0	1
1	2
2	3
3	4

NOTE 2—The number of segments specifier value in Table 16-19 applies to the TxStsNumberSegments and RxStsNumberSegments parameters of the MLME-STS.request primitive specified in 10.29.9.4.1 and to the *phyHrpUwbStsTxSegNum* and *phyHrpUwbStsRxSegNum* attributes.

16.2.9.4 Additional STS RMARKERs (SRMARKERs)

When ranging with packets incorporating the STS, additional RMARKERs are defined relating to the start and end of individual STS segments (if present), as follows:

- SRMARKER0 is the time when the peak of the hypothetical pulse in the first chip of the 512-chip gap before the first STS segment is at the local antenna.
- SRMARKER1 is the time when the peak of the hypothetical pulse in the first chip of the 512-chip gap at the end of the first STS segment (and start of the second STS segment) is at the local antenna.
- SRMARKER2 is the time when the peak of the hypothetical pulse in the first chip of the 512-chip gap at the end of the second STS segment (and start of the third STS segment) is at the local antenna.
- SRMARKER3 is the time when the peak of the hypothetical pulse in the first chip of the 512-chip gap at the end of the third STS segment (and start of the fourth STS segment) is at the local antenna.
- SRMARKER4 is the time when the peak of the hypothetical pulse in the first chip of the 512-chip gap at the end of the fourth STS segment is at the local antenna.

These positions of SRMARKER0 to SRMARKER4 are illustrated in Figure 16-12. In the STS packet configurations one and three, where PHR and PSDU are transmitted after the STS or not at all, the RMARKER and SRMARKER0 are the same.

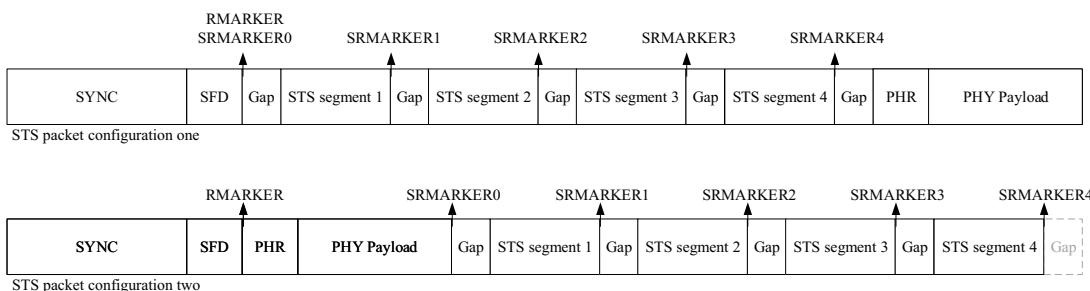


Figure 16-12—Position of STS SRMARKERS

Parameters of the MCPS-DATA primitives defined in 8.3 are defined to report the ranging counter values corresponding to transmission and reception of SRMARKER0 to SRMARKER4, along with FoM values associated with the reception of each. Support for these SRMARKER parameters, and their associated FoM values, is optional.

16.3 Modulation

16.3.1 Modulation mathematical framework

The transmit waveform during the k th symbol interval may be expressed as follows:

$$x^{(k)}(t) = [1 - 2g_1^{(k)}] \sum_{n=1}^{N_{\text{cpb}}} [1 - 2s_{n+kN_{\text{cpb}}}] \times p(t - g_0^{(k)}T_{\text{BPM}} - h^{(k)}T_{\text{burst}} - nT_c)$$

This equation describes the time hopping with polarity scrambling, which improves the interference rejection capabilities of the HRP UWB PHY. The k th symbol interval carries two information bits $g_0^{(k)}$ and $g_1^{(k)} \in \{0, 1\}$. Bit $g_0^{(k)}$ is encoded into the burst position, whereas bit $g_1^{(k)}$ is encoded into the burst polarity. The sequence $s_{n+kN_{\text{cpb}}} \in \{0, 1\}$, $n = 0, 1, \dots, N_{\text{cpb}} - 1$ is the scrambling code used during the k th

symbol interval, $h^{(k)} \in \{0, 1 - N_{hop} - 1\}$ is the k th burst hopping position, and $p(t)$ is the transmitted pulse shape at the antenna input. The burst hopping sequence $h^{(k)}$ provides for multiuser interference rejection. The chip scrambling sequence $s_{n+kN_{cpb}}$ provides additional interference suppression among coherent receivers as well as spectral smoothing of the transmitted waveform. The equation defines the transmitted signal during the valid burst interval; at all other possible burst positions, no signal shall be transmitted.

A reference modulator illustrating the BPM-BPSK modulation is shown in Figure 16-13.

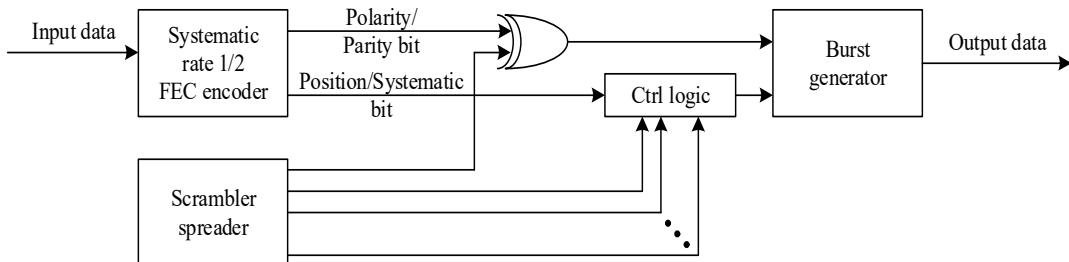


Figure 16-13—Reference modulator

When the Viterbi rate is one, the FEC encoder is replaced by a multiplexer that shall apply even bits to the position input and odd bits to the polarity input.

16.3.2 Spreading

The time-varying spreader sequence $s_{n+kN_{cpb}}$ and the time-varying burst hopping sequence $h^{(k)}$ shall be generated from a common PRBS scrambler.

The polynomial for the scrambler generator shall be $g(D) = 1 + D^{14} + D^{15}$.

where D is a single chip delay, T_c , element. This polynomial forms not only a maximal length sequence, but also it is a primitive polynomial. By the given generator polynomial, the corresponding scrambler output is generated as follows:

$$s_n = s_{n-14} \oplus s_{n-15} \quad n = 0, 1, 2, \dots$$

where \oplus denotes modulo-2 addition.

A LFSR realization of the scrambler is shown in Figure 16-14. The LFSR shall be initialized upon the transmission of bit 0 of the PHR.

NOTE 1— N_{cpb} may change depending on the data rate and PRF in use during the PSDU.

The LFSR shall not be reset after transmission of the PHR.

The initial state of the LFSR shall be determined from the preamble code by first removing all the zeros in the ternary code and then replacing all the negative ones with a zero. The first 15 bits of the resulting binary state shall be loaded into the LFSR. Table 16-20 shows an example of this procedure for preamble code C_6 (length 31, preamble code index 6, as defined in Table 16-7). The table shows the initial state as well as the first 16 output bits from the scrambler.

NOTE 2—Even though each device within a PAN uses the same initial LFSR setting, the communication in WPAN is asynchronous so that the hopping and scrambling provides interference rejection.

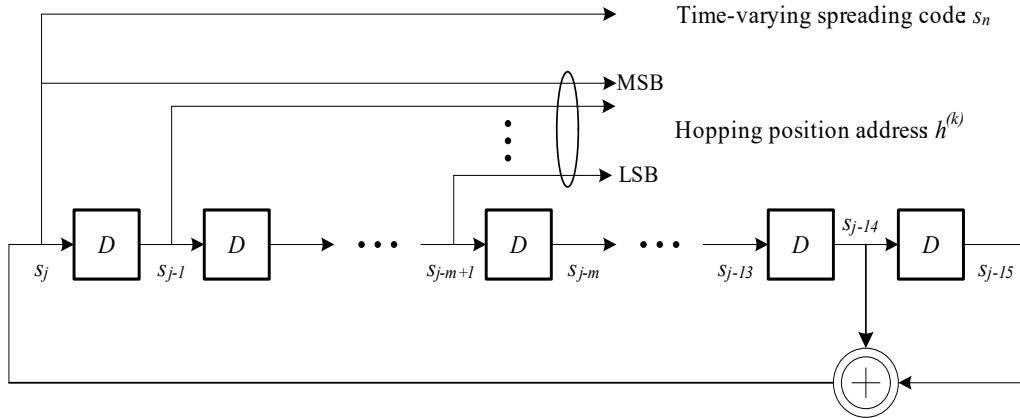


Figure 16-14—LFSR implementation of the scrambler

Table 16-20—Example LFSR initial state for preamble code 6

Initial state ($s_{-15}, s_{-14}, \dots, s_{-1}$)	LFSR output: First 16 bits s_0, s_1, \dots, s_{15} (s_0 first in time)
111000101101101	0010011101101110

The LFSR shall be clocked at the peak PRF of 499.2 MHz as specified in Table 16-4. During the k th symbol interval, the LFSR shall be clocked N_{cpb} times, and the scrambler output shall be the k th scrambling code $s_{n+kN_{\text{cpb}}}$, $n = 0, 1, \dots, N_{\text{cpb}} - 1$. Furthermore, the k th burst hopping position shall be computed as follows:

$$h^{(k)} = 2^0 s_{kN_{\text{cpb}}} + 2^1 s_{1+kN_{\text{cpb}}} + \dots + 2^{m-1} s_{m-1+kN_{\text{cpb}}}$$

where $m = \log_2(N_{\text{hop}})$.

As shown in Table 16-4, the number of hopping burst N_{hop} is always a power of two, and consequently, m is always an integer.

NOTE 3—For $N_{\text{cpb}} < m$, the LFSR is clocked N_{cpb} times, not m times.

For the mandatory modes with mean data PRFs of 15.60 MHz and 3.90 MHz, the numbers of hopping bursts are 8 and 32, respectively, as indicated in Table 16-4, and consequently, m takes on the values 3 and 5, respectively. The corresponding hopping sequences are as follows:

$$h^{(k)} = s_{kN_{\text{cpb}}} + 2s_{1+kN_{\text{cpb}}} + 4s_{2+kN_{\text{cpb}}} \quad \text{Mean PRF} = 15.60 \text{ MHz}$$

$$h^{(k)} = s_{kN_{\text{cpb}}} + 2s_{1+kN_{\text{cpb}}} + 4s_{2+kN_{\text{cpb}}} + 8s_{3+kN_{\text{cpb}}} + 16s_{4+kN_{\text{cpb}}} \quad \text{Mean PRF} = 3.90 \text{ MHz}$$

16.3.3 FEC

16.3.3.1 Overview

The FEC used by the HRP UWB PHY is a concatenated code consisting of an outer Reed-Solomon systematic block code and an inner half-rate systematic convolutional code. The inner convolutional code is not necessarily enabled at all data rates; the rows of Table 16-4 that have a Viterbi rate of one indicate that the inner convolutional code is disabled for the PSDU part of the PHY frame.

The FEC encoding of a block of M PSDU bits, b_0, b_1, \dots, b_{M-1} , is shown in Figure 16-15. The Reed-Solomon encoder shall append 48 parity bits, p_0, p_1, \dots, p_{47} , to the original block. This results in a Reed-Solomon encoded block of length $M + 48$. When the Viterbi rate is 0.5, a half-rate systematic convolutional encoder shall encode the Reed-Solomon encoded block into a systematic coded block of length $2M + 96$ bits. The convolutional systematic bits shall be used to encode the position of the burst, whereas the convolutional parity bits shall be used to encode the polarity of the pulses within a burst. When the Viterbi rate is one, even outputs of the Reed-Solomon encoder ($b_0, b_2, \dots, b_{M-2}, p_0, p_2, \dots, p_{46}$) shall be used to encode the position of the burst, and odd outputs ($b_1, b_3, \dots, b_{M-1}, p_1, p_3, \dots, p_{47}$) shall be used to encode the polarity of the pulses.

NOTE 1—Here M is always an even number.

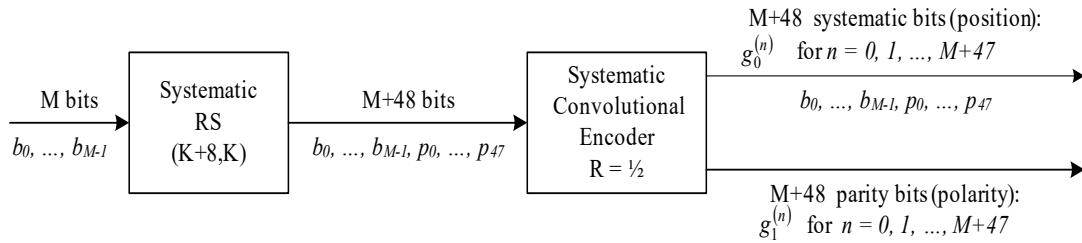


Figure 16-15—FEC encoding process

A noncoherent receiver cannot see the convolutional parity bits (parity bits), and consequently, a noncoherent receiver may use only a Reed-Solomon decoder to improve its performance. A coherent receiver may use either or both Reed-Solomon and convolutional decoding algorithms.

NOTE 2—Here, since both the Reed-Solomon and the convolutional codes are systematic, a receiver (either coherent or noncoherent) may be implemented without an FEC decoder. In this case, the information bits are simply recovered by demodulating the position of the burst. There will be additional parity check bits as a result of the Reed-Solomon encoding, but these may simply be ignored.

16.3.3.2 Reed-Solomon encoding

The systematic Reed-Solomon code is over the Galois field, GF(2^6), which is built as an extension of GF(2). The systematic Reed-Solomon code shall use the following generator polynomial:

$$g(x) = \prod_{k=1}^8 (x + \alpha^k) = x^8 + 55x^7 + 61x^6 + 37x^5 + 48x^4 + 47x^3 + 20x^2 + 6x^1 + 22$$

where $\alpha = 010000$ is a root of the binary primitive polynomial $1 + x + x^6$ in GF(2^6).

In Reed-Solomon encoding RS₆($K + 8, K$), a block of I bits (with $K = \lceil I/6 \rceil$) is encoded into a codeword of $I + 48$ bits. The Reed-Solomon encoding procedure is performed in the following steps:

- a) *Addition of dummy bits.* The block of I information bits is expanded by adding $330 - I$ dummy (zero) bits to the beginning of the block. The expanded block is denoted as $\{d_0, d_1, \dots, d_{329}\}$ where d_0 is the first in time.
- b) *Bit-to-symbol conversion.* The 330 bits $\{d_0, d_1, \dots, d_{329}\}$ are converted into 55 Reed-Solomon symbols $\{D_0, D_1, \dots, D_{54}\}$ having the following polynomial representation:

$$D_k = \alpha^5 d_{6k+5} + \alpha^4 d_{6k+4} + \alpha^3 d_{6k+3} + \alpha^2 d_{6k+2} + \alpha d_{6k+1} + d_{6k}, \text{ where } k = 0: 54$$

Resulting 6-bit symbols are presented as $D_k = \{d_{6k+5}, d_{6k+4}, d_{6k+3}, d_{6k+2}, d_{6k+1}, d_{6k}\}$, where d_{6k+5} is the MSB and d_{6k} is the LSB.

- c) *Encoding.* The information symbols $\{D_0, D_1, \dots, D_{54}\}$ are encoded by systematic RS₆(63,55) code with output symbols $\{U_0, U_1, \dots, U_{62}\}$ ordered as follows:

$$U_k = \begin{cases} D_k & (k = 0, 1, \dots, 54) \\ P_k & (k = 55, 56, \dots, 62) \end{cases}$$

where P_k are parity check symbols added by the RS₆(63,55) encoder.

The information polynomial associated with the information symbols $\{D_0, D_1, \dots, D_{54}\}$ is denoted as $D(x) = x^{54}D_0 + x^{53}D_1 + \dots + xD_{53} + 54$. The parity check polynomial associated with the parity check symbols is denoted as $P(x) = x^7P_{55} + x^6P_{56} + \dots + xP_{61} + P_{62}$. The parity check symbols are calculated as follows:

$$\begin{aligned} P(x) &= \text{remainder}[x^8 D(x) / g(x)] \\ U(x) &= x^8 D(x) + P(x) \end{aligned}$$

- d) *Symbol-to-bit conversion.* The output symbols $\{U_0, U_1, \dots, U_{62}\}$ are converted into binary form with LSB coming out first, resulting in a block of 378 bits $\{u_0, u_1, \dots, u_{377}\}$.
- e) *Removal of dummy bits.* The $330 - I$ dummy bits added in the first step are removed. Only the last $I + 48$ bits are transmitted, i.e., $\{u_{330-I}, u_{331-I}, \dots, u_{377}\}$ with u_{330-I} being first in time.

16.3.3.3 Convolutional encoding

The inner convolutional encoder shall use the $K = 3$ rate $R = 1/2$ code with generator polynomials $g_0 = [010]_2$ and $g_1 = [101]_2$, as shown in Figure 16-16. Upon transmission of each PPDU, the encoder shall be initialized to the all zero state. Additionally, the encoder shall be returned to the all zero state by appending two zero bits to the PPDU.

NOTE—Since the generator polynomials are systematic, they are also noncatastrophic.

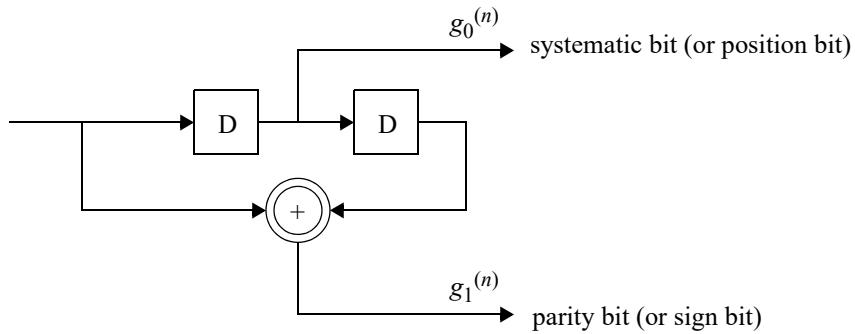


Figure 16-16— $K = 3$ systematic convolutional encoder

The HRP-ERDEV in its HPRF mode may optionally employ the $K = 3$ convolutional encoder, with the generator polynomials (133,171), as shown in Figure 16-17. Before transmission of each PPDU, this encoder shall be initialized to the all zero state. Additionally, this encoder shall be returned to the all zero state by separately appending six zero bits to both the PHR and the PSDU. When employing this convolutional encoder the Reed-Solomon coding specified in 16.3.3.2 shall not be applied to the PSDU.

The selection between the $K = 3$ and $K = 7$ convolution coding is achieved by setting the *phyHrpUwbCcConstraintLength* attribute to value CL3 or CL7, respectively.

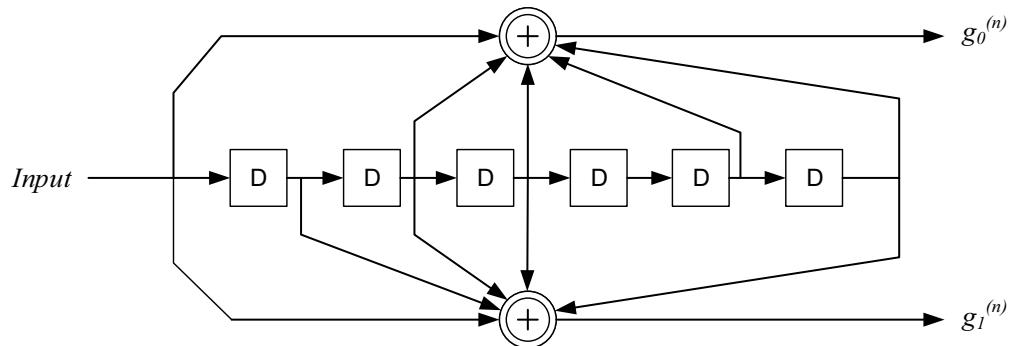


Figure 16-17—Optional HRP-ERDEV $K = 7$ convolutional encoder

16.3.4 HRP-ERDEV modulation in HPRF mode

16.3.4.1 Introduction

The HRP-ERDEV in its HPRF mode shall support both modulations described in 16.3.4.2 and 16.3.4.3. The modulation parameters of these are summarized in Table 16-21.

Table 16-21—HRP-ERDEV HPRF mode modulation parameters

# Pulses per data symbol	# Chips per data symbol	Peak PRF (MHz)	Mean PRF (MHz)	Data symbol duration (ns)	Data symbol rate (MHz)	Bit rate, RS used (Mb/s)	Bit rate, RS not used (Mb/s)
8	16	499.2	249.6	32.05	31.2	27.24	31.2
16	64	249.6	124.8	128.21	7.8	6.81	7.8

These modulations apply to both the PHR and the PSDU, as described in 16.3.4.2 and 16.3.4.3. The selection of modulation and the resultant bit rates for the PHR and PSDU are determined by settings of the *phyHrpUwbPhrDataRate* and *phyHrpUwbCcConstraintLength* attributes as specified in Table 16-22.

Table 16-22—PHR and PSDU data rates for the HRP-ERDEV in HPRF mode

Value of the <i>phyHrpUwbPhrDataRate</i> attribute	Value of the <i>phyHrpUwbCcConstraintLength</i> attribute	PHR bit rate (Mb/s)	PSDU bit rate (Mb/s)
DRHM_LR	CL3	3.9	6.8
DRHM_LR	CL7	7.8	7.8
DRHM_HR	CL3	15.6	27.2
DRHM_HR	CL7	31.2	31.2

16.3.4.2 Modulation at 249.6 MHz PRF

This modulation has eight pulses per coded bit separated into two groups of four sent at the peak 499.2 MHz chipping rate, each group followed by a 4 chip guard interval, as shown in Figure 16-18 where the vertical double-headed arrows indicate the pulse positions. For the PHR the modulation rate is halved to use 16 pulses per coded bit in four groups of four sent at the peak 499.2 MHz chipping rate, each followed by a 4 chip guard interval, as shown in Figure 16-19.

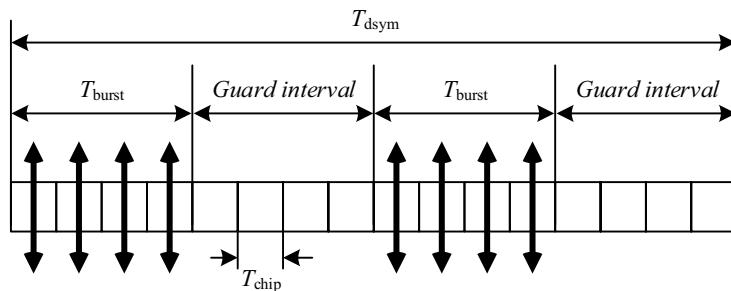


Figure 16-18—HRP-ERDEV data symbol structure at 249.6 MHz PRF

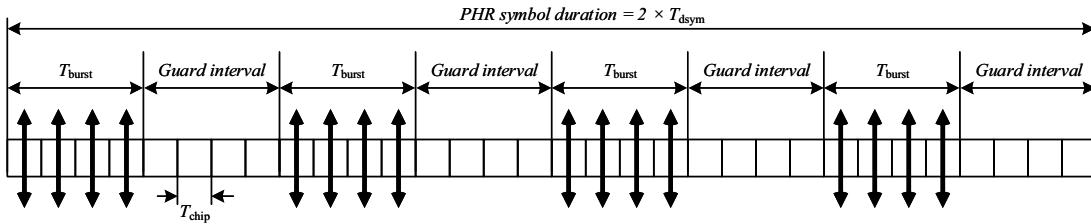


Figure 16-19—HRP-ERDEV PHR symbol structure at 249.6 MHz PRF

When employing the optional HRP-ERDEV convolutional encoder, the data modulation shown in Figure 16-18 shall apply to both PHR and PSDU.

The $g_0^{(n)}$ and $g_1^{(n)}$ output of the convolutional encoder specified in 16.3.3.3 shall be mapped onto the burst bit patterns specified in Table 16-23 and scrambled by the time-varying spreading code s_n as specified in 16.3.2 before being sent as pulses as per 16.3.1, (i.e., zero is positive polarity and one is negative polarity). When employing the optional HRP-ERDEV convolutional encoder the burst bit patterns shall be as specified in Table 16-24.

Table 16-23—Symbol mapping at 249.6 MHz PRF

$g_0^{(n)}$	$g_1^{(n)}$	First burst	Second burst	(PHR only) third burst	(PHR only) fourth burst
0	0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0
1	0	1 1 1 1	0 0 0 0	1 1 1 1	0 0 0 0
0	1	1 1 1 1	1 1 1 1	1 1 1 1	1 1 1 1
1	1	0 0 0 0	1 1 1 1	0 0 0 0	1 1 1 1

Table 16-24—Symbol mapping at 249.6 MHz PRF for the optional convolutional encoder

$g_0^{(n)}$	$g_1^{(n)}$	First burst	Second burst
0	0	0 0 0 0	0 0 0 0
1	0	1 1 1 1	0 0 0 0
0	1	0 0 0 0	1 1 1 1
1	1	1 1 1 1	1 1 1 1

For this 249.6 MHz PRF data modulation, with the mandatory Reed-Solomon coding the data modulation rate is approximately 27 Mb/s. When employing the optional HRP-ERDEV convolutional encoder (where Reed-Solomon coding is not applied) the resultant data modulation rate is approximately 31 Mb/s.

16.3.4.3 Modulation at 124.8 MHz PRF

This modulation has 16 pulses per coded bit separated into two groups of eight sent at half the peak 499.2 MHz chipping rate, each group followed by a 16 chip guard interval, as shown in Figure 16-20, where the vertical double-headed arrows indicate the active pulse positions. For the PHR the modulation rate is

halved to use 32 pulses per coded bit in four groups of eight sent at half the peak 499.2 MHz chipping rate, each followed by a 16 chip guard interval, as shown in Figure 16-21.

When employing the optional HRP-ERDEV convolutional encoder, the data modulation shown in Figure 16-20 shall apply to both PHR and PSDU.

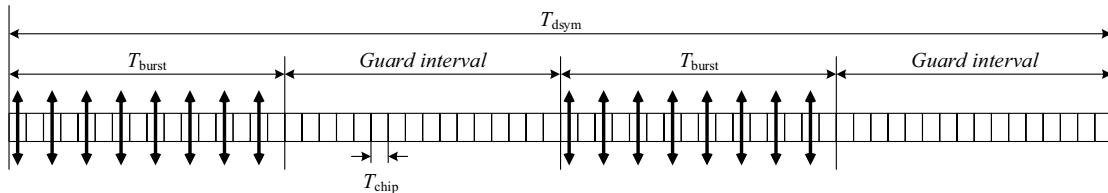


Figure 16-20—HRP-ERDEV data symbol structure at 124.8 MHz PRF

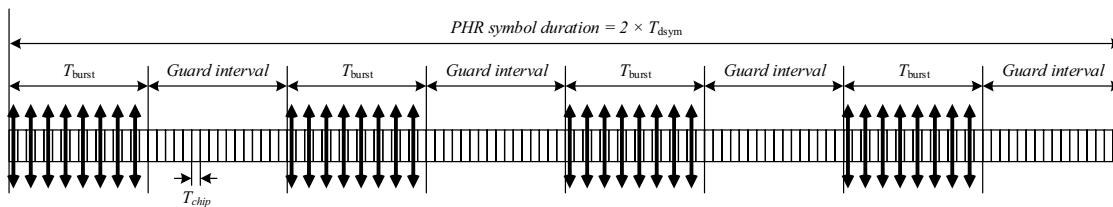


Figure 16-21—HRP-ERDEV PHR symbol structure at 124.8 MHz PRF

The $g_0^{(n)}$ and $g_1^{(n)}$ output of the convolutional encoder specified in 16.3.3.3 shall be mapped onto the burst bit patterns specified in Table 16-25 and scrambled by the time-varying spreading code s_n as specified in 16.3.2 before being sent as pulses as per 16.3.1, (i.e., zero is positive polarity and one is negative polarity). When employing the optional HRP-ERDEV convolutional encoder the burst bit patterns shall be as specified in Table 16-26.

Table 16-25—Symbol mapping at 124.8 MHz PRF

$g_0^{(n)}$	$g_1^{(n)}$	First burst	Second burst	(PHR only) third burst	(PHR only) fourth burst
0	0	0 0 0 0 0 0 0 0	0 0 0 0 0 0 0	0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0
1	0	1 1 1 1 1 1 1 1	0 0 0 0 0 0 0	1 1 1 1 1 1 1 1	0 0 0 0 0 0 0 0
0	1	1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1
1	1	0 0 0 0 0 0 0 0	1 1 1 1 1 1 1 1	0 0 0 0 0 0 0 0	1 1 1 1 1 1 1 1

Table 16-26—Symbol mapping at 124.8 MHz PRF for the optional convolutional encoder

$g_0^{(n)}$	$g_1^{(n)}$	First burst	Second burst
0	0	0 0 0 0 0 0 0 0	0 0 0 0 0 0 0
1	0	1 1 1 1 1 1 1 1	0 0 0 0 0 0 0
0	1	0 0 0 0 0 0 0 0	1 1 1 1 1 1 1 1
1	1	1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1

For this 124.8 MHz PRF data modulation, with the mandatory Reed-Solomon coding the data modulation rate is approximately 6.8 Mb/s. When employing the optional HRP-ERDEV convolutional encoder (where Reed-Solomon coding is not applied) the resultant data modulation rate is approximately 7.8 Mb/s.

16.4 RF requirements

16.4.1 Operating frequency bands

The set of operating frequency bands is defined in Table 16-27. For the sub-gigahertz operation, channel 0 is defined as the mandatory channel; for the low-band operation, channel 3 is the mandatory channel; and for the high-band operation, channel 9 is the mandatory channel.

Table 16-27—HRP UWB PHY band allocation

Band group^a (decimal)	Channel number (decimal)	Center frequency, f_c (MHz)	Band width (MHz)	Mandatory/Optional
0	0	499.2	499.2	Mandatory below 1 GHz
1	1	3494.4	499.2	Optional
	2	3993.6	499.2	Optional
	3	4492.8	499.2	Mandatory in low band
	4	3993.6	1331.2	Optional
2	5	6489.6	499.2	Optional
	6	6988.8	499.2	Optional
	7	6489.6	1081.6	Optional
	8	7488.0	499.2	Optional
	9	7987.2	499.2	Mandatory in high band
	10	8486.4	499.2	Optional
	11	7987.2	1331.2	Optional
	12	8985.6	499.2	Optional
	13	9484.8	499.2	Optional
	14	9984.0	499.2	Optional
	15	9484.8	1354.97	Optional

^a Note that bands indicate a sequence of adjacent HRP UWB center frequencies: band 0 is the sub-gigahertz channel, band 1 has the low-band HRP UWB channels, and band 2 has the high-band channels.

Figure 16-22 is a graphical representation of the data presented in Table 16-27. Each HRP UWB PHY channel is shown as a heavy black line centered on the channel's center frequency. The length of the lines depicts the channel bandwidth.

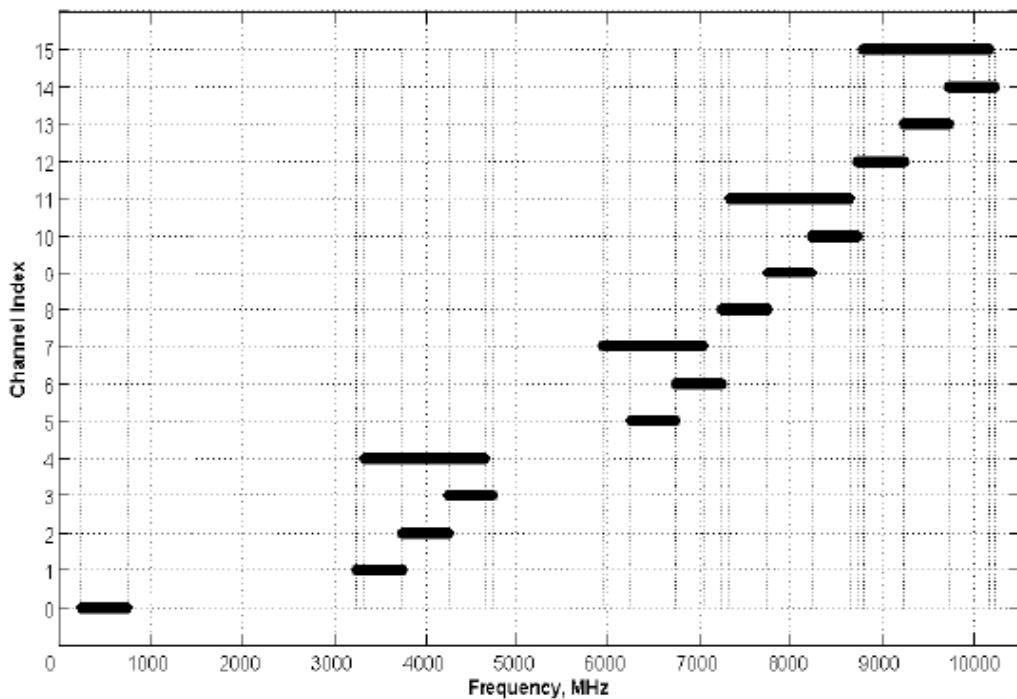


Figure 16-22—HRP UWB PHY band plan

16.4.2 Channel assignments

A total of 32 complex channels are assigned for operation, two channels in each of the 16 defined operating frequency bands. A compliant implementation shall support at least the two channels for one of the mandatory bands.

16.4.3 Regulatory compliance

The maximum allowable output PSD shall be in accordance with practices specified by the appropriate regulatory bodies.

16.4.4 Baseband impulse response

The transmitted pulse shape $p(t)$ shall be constrained by the shape of its cross-correlation function with a standard reference pulse, $r(t)$. The normalized cross-correlation between two waveforms is defined as follows:

$$\phi(\tau) = \frac{1}{\sqrt{E_r E_p}} \operatorname{Re} \int_{-\infty}^{\infty} r(t) p^*(t + \tau) dt$$

where E_r and E_p are the energies of $r(t)$ and $p(t)$, respectively, p^* denotes the complex conjugate of p , and, Re indicates that the real part is used. The reference $r(t)$ pulse used in the calculation of $|\phi(\tau)|$ is a root raised cosine pulse with a roll-off factor of $\beta = 0.5$. Mathematically this is as follows:

$$r(t) = \frac{4\beta}{\pi\sqrt{T_p}} \frac{\cos[(1+\beta)\pi t/T_p] + \frac{\sin[(1-\beta)\pi t/T_p]}{4\beta(t/T_p)}}{1 - (4\beta t/T_p)^2}$$

where T_p is the inverse of the chip frequency. Table 16-28 shows the required pulse duration for each channel.

Table 16-28—Required reference pulse durations in each channel

Channel number	Pulse duration, T_p (ns)	Main lobe width, T_w (ns)
{0:3, 5:6, 8:10, 12:14}	2.00	0.5
7	0.92	0.2
{4, 11}	0.75	0.2
15	0.74	0.2

In order for an HRP UWB PHY transmitter to be compliant with this standard, the transmitted pulse $p(t)$ shall have a magnitude of the cross-correlation function $|\phi(\tau)|$ whose main lobe is greater than or equal to 0.8 for a duration of at least T_w , as defined in Table 16-28, and any sidelobe shall be no greater than 0.3. For the purposes of testing a pulse for compliance, the following are defined: Let $|\phi(\tau)|$ be the magnitude of the cross-correlation of $p(t)$ and $r(t)$, and let τ_i , for $i = 1, 2, \dots$, be a set of critical points as follows:

$$\frac{d}{d\tau} |\phi(\tau)| \Big|_{\tau = \tau_i} = 0$$

The maximum of the function occurs at one of these critical points, τ_{max} , where $|\phi(\tau_{max})| \geq |\phi(\tau)|$ for all values of τ . The requirement thus states that for some continuous set of values that contain the point τ_{max} the function $|\phi(\tau)|$ is greater than 0.8. In addition, the second constraint on the value of sidelobes may be stated mathematically as $|\phi(\tau_i)| \leq 0.3$ for all τ_i .

Figure 16-23 shows an example HRP UWB-compliant pulse, $p(t)$ (left plot), along with the root raised cosine reference pulse $r(t)$ (middle plot) with $T_p = 2.0$ ns and the magnitude of the cross-correlation $|\phi(\tau)|$ (right plot). The pulse $p(t)$ is the impulse response of an 8th order Butterworth filter with a 3 dB bandwidth of 500 MHz. Figure 16-23 is intended to show that this example pulse meets the requirements for compliance. Specifically, the main lobe is above 0.8 for nearly 1 ns, and no sidelobe is greater than 0.3 (in this case, the largest sidelobe peak is 0.2). The pulse $p(t)$ is a compliant pulse for channels {0:3, 5:6, 8:10, 12:14}.

NOTE—It is not the intention of this standard to imply that pulse shaping only occurs at baseband, but rather that the measurements described here occur on the pulse envelope if shaping is done at passband.

To help with interoperability in ranging scenarios, it is recommended that the RDEV supports a mode in which the transmitted pulse exhibits minimum precursor energy.

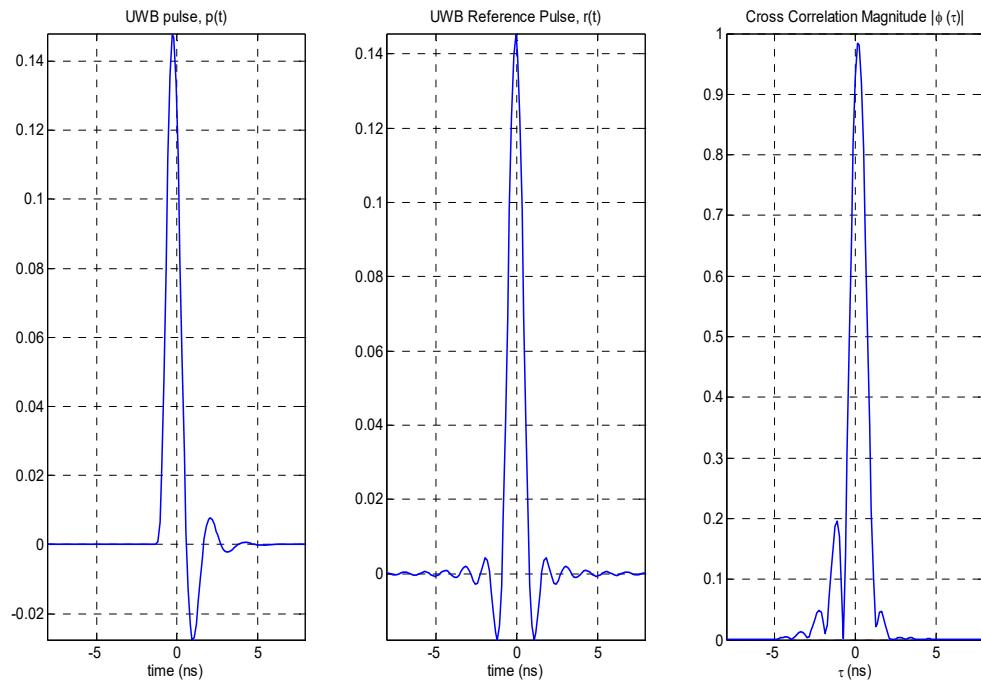


Figure 16-23—Compliant pulse example

For a device electing to use a pulse with precursor, it is recommended that the transmitted pulse follows the mathematical formula of the reference root raised cosine pulse $r(t)$ with a roll-off factor of $\beta = 0.45$, over at least ± 3 chip periods.

If the transmitted pulse follows the minimum precursor pulse recommendation, the transmitted pulse shape $p(t)$ should be constrained by the time domain mask of Figure 16-24, where the peak magnitude of the pulse is scaled to a value of one, and the time unit is T_p , defined in Table 16-28. The pulse should monotonically rise to a first peak amplitude; the first peak amplitude is defined as the maximum amplitude of the pulse before it first drops more than 1.25%.

It is further recommended that some method, for example an out-of-band means or an upper layer message, is used to indicate whether an ERDEV's transmitter is employing a minimum precursor pulse or a pulse with precursors. This information might be used by receiving ERDEVs to improve the accuracy of their RMARKER arrival estimates, and/or to correctly reflect the expected accuracy level in the reported FoM value. In some circumstances additional performance benefits can be obtained if the receiver is provided with the shape of the minimum precursor pulse being used by the transmitter.

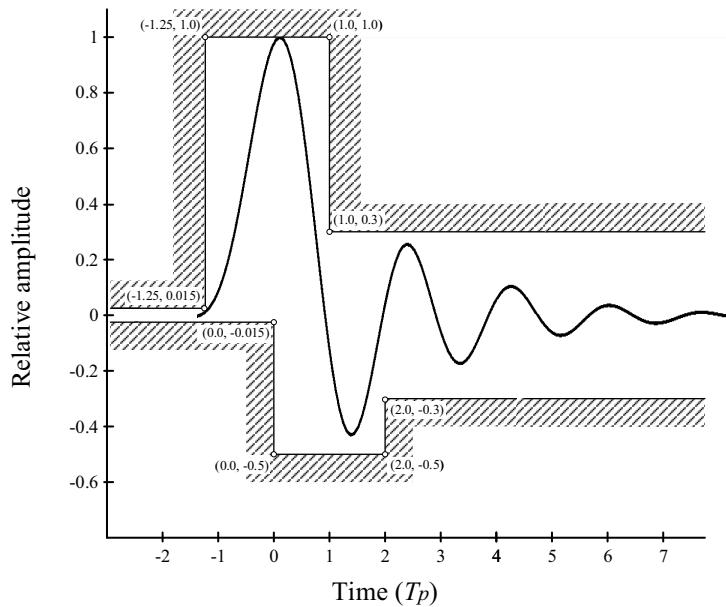


Figure 16-24—Recommended time domain mask for the HRP UWB PHY pulse

16.4.5 Transmit PSD mask

The transmitted spectrum shall be less than -10 dB relative to the maximum spectral density of the signal for $0.65/T_p < |f - f_c| < 0.8/T_p$ and -18 dB for $|f - f_c| > 0.8/T_p$. For example, the transmit spectrum mask for channel 4 is shown in Figure 16-25. The measurements shall be made using a 1 MHz resolution bandwidth and a 1 kHz video bandwidth.

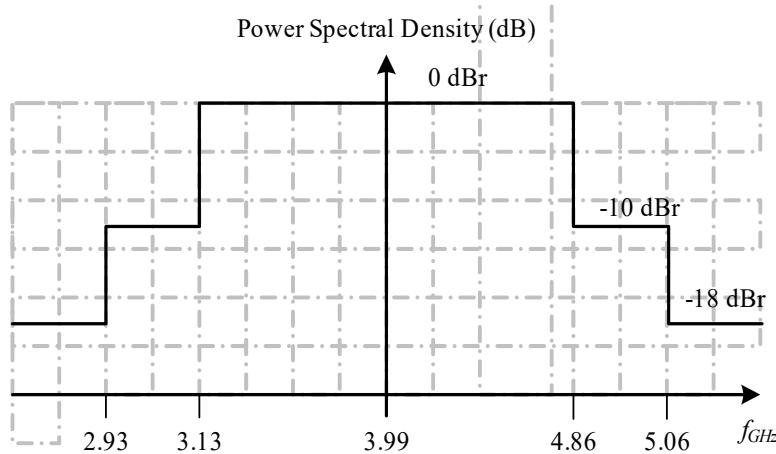


Figure 16-25—Transmit spectrum mask for band 4

16.4.6 Chip rate clock and chip carrier alignment

An HRP UWB transmitter shall be capable of chipping at the peak PRF given in Table 16-4 with an accuracy of $\pm 20 \times 10^{-6}$. In addition, for each HRP UWB PHY channel, the center of transmitted energy shall be within the values listed in Table 16-27 also with an accuracy of $\pm 20 \times 10^{-6}$. The measurements shall

be made using a 1 MHz resolution bandwidth and a 1 kHz video bandwidth. The carrier center frequency and the chip rate frequency shall be derived from the same reference oscillator.

16.4.7 TX-to-RX turnaround time

The HRP UWB PHY shall have a TX-to-RX turnaround time as defined in 11.2.2.

16.4.8 RX-to-TX turnaround time

The HRP UWB PHY shall have an RX-to-TX turnaround time as defined in 11.2.3.

16.4.9 Transmit center frequency tolerance

The HRP UWB PHY transmit center frequency tolerance shall be $\pm 20 \times 10^{-6}$. The tolerance on the chipping clock given in 16.4.6 takes precedence over this requirement.

16.4.10 Receiver maximum input level of desired signal

The HRP UWB PHY shall have a receiver maximum input level greater than or equal to -45 dBm/MHz, using the measurement defined in 11.2.5.

16.4.11 Receiver ED

The HRP UWB PHY shall provide the receiver ED measurement as described in 11.2.6. The averaging period for the receiver ED measurement is implementation specific.

The ED measurement for each channel may be performed as a series of measurements, each made at a fraction of the total channel bandwidth, in which case *phyHrpUwbScanBinsPerChannel* specifies the number of frequency increments used. When this value is greater than one, the ED result reported using the MLME-SCAN.confirm primitive shall be a list of ED measurements, one for each frequency increment measurement. An implementation may provide multiple ED measurements, for example, to provide information to a higher layer that detects non-HRP UWB services for the purpose of active detect and avoid (DAA) procedures as may be required in some environments.

16.4.12 LQI

The HRP UWB PHY shall provide the LQI measurement as described in 11.2.7.

16.4.13 CCA

For CCA mode 6, the CCA detection time for the HRP UWB PHY shall be equal to 40 mandatory symbol periods, which includes at least 8 (multiplexed) preamble symbols, as described in 16.6.

16.5 HRP UWB PHY optional pulse shapes

16.5.1 Overview

The HRP UWB PHY offers the capability to transmit several optional pulse types. The use of these options is controlled by the PAN coordinator and shall be limited to the nonbeacon frames. In other words, beacon frames shall be transmitted using the mandatory pulse shape as defined in 16.4.4, but all other frames may be transmitted using the optional pulse shapes if all devices in the PAN are capable of supporting the optional pulse shapes. PANs that use the optional pulse shapes shall indicate the use of a specific option via the *phyHrpUwbCurrentPulseShape* PIB attribute. Devices choosing to join a PAN using one of the optional

pulse shapes should make their decision based on the value of *phyHrpUwbCurrentPulseShape* that is reported during the scan procedure.

16.5.2 HRP UWB PHY optional chirp on UWB (CoU) pulses

The purpose of chirp on ultra wideband (CoU) pulses is to provide an additional dimension (besides frequency and DS codes) to support simultaneously operating piconets. Because CoU is an optional mode of pulse shapes in addition to the mandatory pulse shape, all modulation specifications shall be the same as they are for the mandatory pulse shape except those defined for the CoU pulses when a device implements the CoU option.

A mathematical representation of a CoU pulse at baseband is as follows:

$$p_{CoU}(t) = \begin{cases} p(t) \exp\left(-j\frac{\pi\beta t^2}{2}\right) & -\frac{T}{2} \leq t \leq \frac{T}{2} \\ 0 & \text{otherwise} \end{cases}$$

where

$p(t)$ denotes a mandatory pulse shape that satisfies constraints in 16.4.4.

$\beta = B/T$ is the chirping rate (chirping slope). Moreover, B and T are the bandwidth and time duration of the CoU pulse, respectively.

A graphical example of CoU pulse is shown in Figure 16-26.

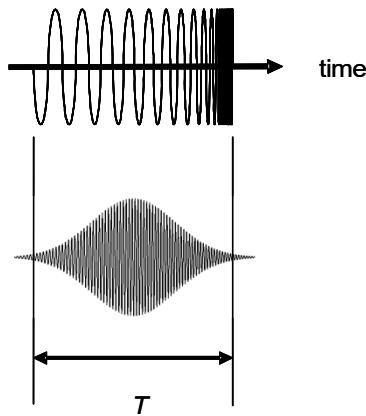


Figure 16-26—Graphical view of a CoU pulse

The CoU is an operation added to the mandatory pulse. When a CoU pulse is transmitted, the receiver needs to perform a matched de-chirp operation to demodulate the signal.

The optional CoU pulses are admitted with two slopes per each DS code per each 500 MHz bandwidth. The chirp slopes are denoted as CCh.1 and CCh.2. Within channels 4, 7, 11, and 15, there are chirp slopes admitted per each DS code. These are denoted as CCh.3 through CCh.6. The values for each chirp slope are listed in Table 16-29.

Table 16-29—CoU channel slopes

CoU number	β (slopes)
CCh.1	500 MHz/2.5 ns
CCh.2	-500 MHz/2.5 ns
CCh.3	1 GHz/5 ns
CCh.4	-1 GHz/5 ns
CCh.5	1 GHz/10 ns
CCh.6	-1 GHz/10 ns

16.5.3 HRP UWB PHY optional continuous spectrum (CS) pulses

This subclause specifies optional CS pulses. A CS pulse is obtained by passing the mandatory pulse through an all-passing CS filter. The CS filter introduces controlled group delays to the input pulse. The purpose of the optional CS pulses is to reduce the interference level between different PANs.

Since CS is an optional mode of pulse shapes in addition to the mandatory pulse shape, all modulation specifications shall be the same as they are for the mandatory pulse shape except those defined for the CS pulses when a device implements the CS option.

An optional CS pulse $p_{CS}(t)$ is defined as shown below:

$$p_{CS}(t) = \int P(f) \exp[-j2\pi f(t - (\tau \times f))] df$$

where

- τ represents the group delay (s/Hz)
- $P(f)$ represents the Fourier transform of $p(t)$, where $p(t)$ is any pulse shape that meets the requirements defined in 16.4.4

The Fourier transform is defined as shown below:

$$P(f) = \int p(t) \exp[-j2\pi ft] dt$$

The CS filtering is an operation added to the mandatory pulse. When a CS pulse is transmitted, the receiver needs to perform an inverse CS filtering operation to demodulate the signal.

Some examples of CS pulses are shown in Figure 16-27.

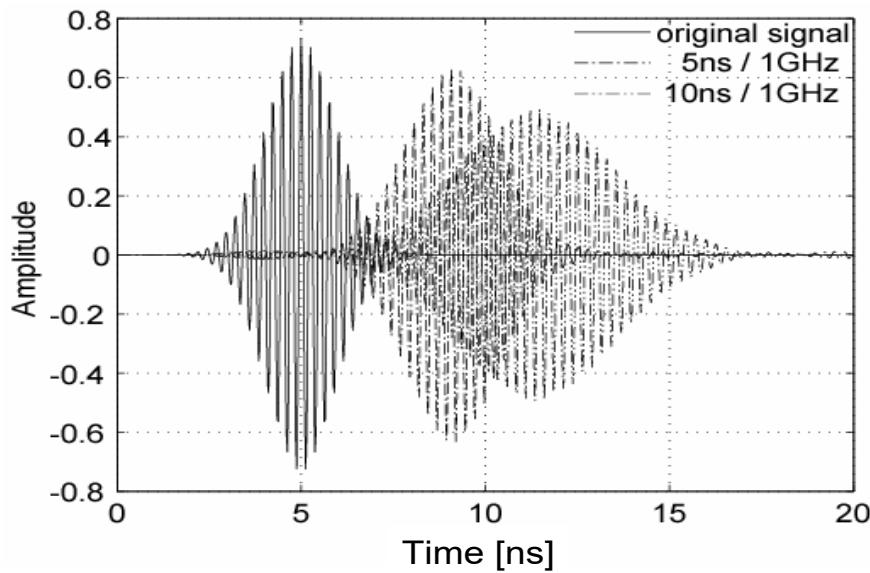


Figure 16-27—Examples of CS pulses

Each 500 MHz band shall use No.1 or No.2 pulses, while each 1.5 GHz band shall use one of No.3 through No.6 pulses, as defined in Table 16-30.

Table 16-30—CS group delays

CS pulse number	τ (Group delay)
No.1	2 ns/500 MHz
No.2	-2 ns/500 MHz
No.3	5 ns/1 GHz
No.4	-5 ns/1 GHz
No.5	10 ns/1 GHz
No.6	-10 ns/1 GHz

16.5.4 HRP UWB PHY linear combination of pulses (LCP)

Linear combination of pulses (LCP) is an optional pulse shape that can be used in regulatory regions where DAA schemes are required by regulators. Using LCP pulses enables a PAN to limit interference to incumbent wireless systems. The pulse shape for LCP is denoted $p_{LCP}(t)$ and is the sum of N weighted and delayed pulses $p(t)$ as follows:

$$p_{LCP}(t) = \sum_{i=1}^N a_i p(t - \tau_i)$$

where $p(t)$ is any pulse that satisfies the cross-correlation constraints outlined in 16.4.4.

The number of pulses N that can be combined is set to four (although smaller number of pulses can be realized by setting the amplitudes of some of the pulses to zero). The values of the pulse delays shall be limited to $0 \leq \tau_i \leq 4$ ns. The value of τ_1 is assumed to be zero, and thus, the remaining delays are considered as relative delay time with respect to the nominal pulse location. The values for these delays are stored as the PIB values $phyHrpUwbLcpDelay2$, $phyHrpUwbLcpDelay3$, and $phyHrpUwbLcpDelay4$. The values for the amplitudes a_i are stored as the PIB values $phyHrpUwbLcpWeight1$ through $phyHrpUwbLcpWeight4$, as defined in Table 12-8. The amplitudes, a_i , shall be selected so that the energy in the combined pulse is the same as the energy in the mandatory pulse. The numerical values of the delays and amplitudes of the pulses shall be transmitted following the general framework of optional pulse shapes, as defined in 16.5. The method to compute the weights and delay values is outside the scope of this standard.

16.6 Extended preamble for optional CCA mode 6

The PHY may provide the capability to perform the optional CCA mode 6, as defined in 11.2.8. This CCA mode shall be supported by the modified frame structure where preamble symbols are multiplexed with the data symbols in the PHR field and the PHY Payload field of a frame.

Figure 16-28 shows the modified frame structure with multiplexed preamble symbols. One preamble symbol is inserted after each PHR and PHY Payload segment. The inserted preamble symbol shall be the same as the symbol used in the SHR, as described in 16.2.6.2, of the same frame. The time interval between two neighboring inserted preamble symbols, which is also the time duration of each PHR or PHY Payload segment, is independent of the current data rate. The PIB attribute $phyHrpUwbInsertedPreambleInterval$ defines a constant time interval based on the data rate of 850 kb/s for all operation bands. The data rate of 850 kb/s is listed in Table 16-12 with the data rate field index of 01. The value of the PIB attribute $phyHrpUwbInsertedPreambleInterval$ is fixed to four. Distinguished from the CCA in narrowband systems, which is used to detect the energy of carrier waveforms, CCA mode 6 is based on the frame with multiplexed preamble is used to detect the presence of preamble symbols. The processing gain can be enhanced by exploiting the spreading characteristics and repetition of the preamble symbols.

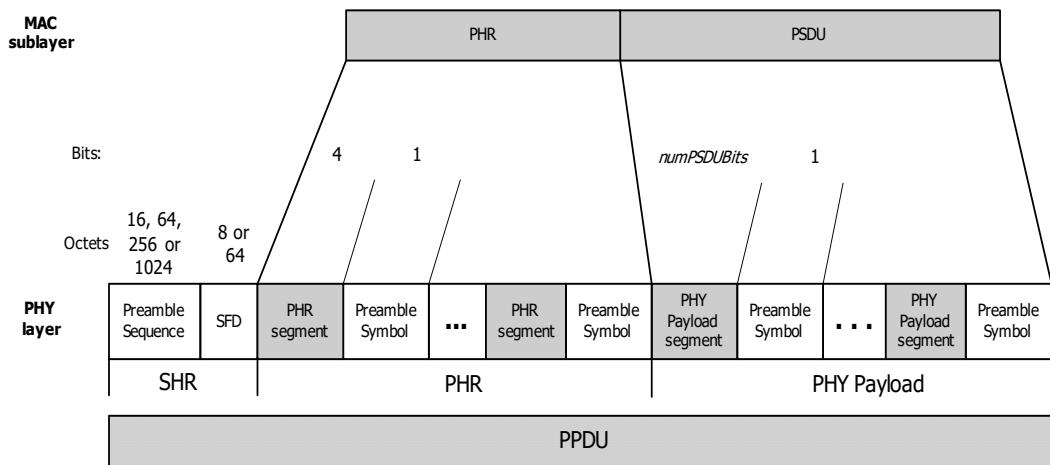


Figure 16-28—Illustration of the modified frame structure with multiplexed preamble

The PAN coordinator of a PAN shall coordinate all nodes in the PAN before the CCA mode 6 is enabled. The modified frame structure with multiplexed preamble shall be applied to a Data frame or a MAC Command frame in the CAP only when the CCA mode 6 is enabled.

The CCA detection time shall be equivalent to 40 data symbol periods, T_{dsym} , for a nominal 850 kb/s, or equivalently, at least 8 (multiplexed) preamble symbols should be captured in the CCA detection time.

In addition to enabling the CCA mode 6, the multiplexed preamble symbols can help to improve ranging accuracy or assist data demodulation. This function is similar to that of the pilot tone in narrowband systems.

16.7 HRP-ERDEV parameter sets

The HRP-ERDEV includes a number of mandatory elements, combinations of which represent a large set of operating modes. Table 16-31 and Table 16-32 specify the mandatory set of operating modes, which includes combinations of parameters suitable for typical use cases. Combinations that are not included are optional.

Table 16-31—Mandatory BPRF mode operating parameter sets

BPRF set #	SYNC PSR	SFD # per Table 16-11	SFD length	STS number of segments	STS segment length (units of 512 chips)	PHR + data	Data rate (Mb/s)	Description
1	64	0	8	0	n/a	Yes	6.8	STS packet configuration 0: SHR, PHR and Data.
2	64	2	8	0	n/a	Yes	6.8	STS packet configuration 1: SHR, STS, PHR and Data.
3	64	2	8	1	64	Yes	6.8	STS packet configuration 2: SHR, STS, PHR and Data.
4	64	2	8	1	64	No	n/a	STS packet configuration 3: SHR, STS only.

With respect to the mandatory operating parameter sets listed in Table 16-31, the HRP-ERDEV shall support all data payload of all lengths from 0 up to the maximum 127 octets that can be specified by the PHR in BPRF mode (see 16.2.7.2), and shall support the preamble symbol codes for the code index values of 9, 10, 11, and 12 specified in Table 16-8.

Table 16-32—Mandatory HPRF mode operating parameter sets

HPRF set #	SYNC PSR	SFD # per Table 16-11	SFD length	STS number of segments	STS segment length (units of 512 chips)	PHR + data	Data rate (Mb/s)	Description
1	64	2	8	0	n/a	Yes	6.8	STS packet configuration 0: SHR, PHR and Data
2	32	2	8	0	n/a	Yes	6.8	
3	32	2	8	0	n/a	Yes	27.2	
4	32	1	4	0	n/a	Yes	27.2	

Table 16-32—Mandatory HPRF mode operating parameter sets (*continued*)

HPRF set #	SYNC PSR	SFD # per Table 16-11	SFD length	STS number of segments	STS segment length (units of 512 chips)	PHR + data	Data rate (Mb/s)	Description
5	64	2	8	2	32	Yes	6.8	STS packet configuration 1: SHR, STS, PHR and Data (lower data rate)
6	64	2	8	1	64	Yes	6.8	
7	64	2	8	2	64	Yes	6.8	
8	32	2	8	1	32	Yes	6.8	
9	32	2	8	2	32	Yes	6.8	
10	32	2	8	1	64	Yes	6.8	
11	32	2	8	2	64	Yes	6.8	
12	64	2	8	1	128	Yes	6.8	
13	64	2	8	2	128	Yes	6.8	
14	32	2	8	1	64	Yes	27.2	
15	32	2	8	2	64	Yes	27.2	STS packet configuration 1: SHR, STS, PHR and Data (higher data rate)
16	32	2	8	1	32	Yes	27.2	
17	32	2	8	2	32	Yes	27.2	
18	32	1	4	1	32	Yes	27.2	
19	32	1	4	2	32	Yes	27.2	
20	64	3	16	1	128	No	n/a	STS packet configuration 3: SHR, STS only.
21	64	3	16	2	128	No	n/a	
22	64	2	8	1	128	No	n/a	
23	64	2	8	2	128	No	n/a	
24	64	2	8	1	64	No	n/a	
25	64	2	8	2	32	No	n/a	
26	32	2	8	1	64	No	n/a	
27	32	2	8	2	64	No	n/a	
28	32	2	8	1	32	No	n/a	
29	32	2	8	2	32	No	n/a	
30	32	1	4	1	32	No	n/a	
31	32	1	4	2	32	No	n/a	

With respect to the mandatory operating parameter sets listed in Table 16-32, the HRP-ERDEV shall support all data payload of all lengths from 0 up to the maximum 1023 octets that can be specified by the PHR in HPRF mode (see 16.2.7.3), and shall support all the preamble symbol codes specified in Table 16-9. The HRP-ERDEV should furthermore support an HPRF operating mode where the SYNC PSR is 32, the SFD # per Table 16-11 is 2 (SFD length of 8), the STS number of segments is 1, the STS segment length (in units of 512 chips) is 16, and where there are no PHR/Data fields.

Reference vectors capturing the above mandatory sets along with a number of optional parameter selections are provided in “15.4z HRP UWB PHY Test Vectors” [B1] with a description of these in Lafer and Leong [B21].

17. GFSK PHY

17.1 PPDU formats

The GFSK PHY shall use the PPDU format described in 13.1, except that the Preamble field is 32 symbols (4 octets) and the bits in each octet shall be “01010101”.

17.2 Modulation

17.2.1 GFSK PHY data rates

The data rate of the GFSK PHY shall be 100 kb/s.

17.2.2 Reference modulator diagram

The functional block diagram in Figure 17-1 is provided as a reference for specifying the GFSK PHY modulation and spreading functions. Each bit in the PPDU shall be processed through the data whitening and modulation functions in octet-wise order, beginning with the Preamble field and ending with the last octet of the PSDU. Within each octet, the LSB, b0, is processed first and the MSB, b7, is processed last.

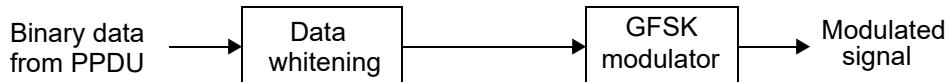


Figure 17-1—GFSK modulation and data whitening functions

17.2.3 Data whitening

Data whitening shall be the exclusive OR of the PHY Payload field with the PN9 sequence. This shall be performed by the transmitter and is as follows:

$$E_n = R_n \oplus \text{PN9}_n$$

where

R_n is the data bit being whitened

E_n is the whitened bit

PN9_n is the PN9 sequence bit

For each packet transmitted with data whitening, R_0 is the first bit of the PSDU and index n increments for subsequent bits of the PSDU. The receiver decodes the scrambled data in the following way:

$$R_n = RE_n \oplus \text{PN9}_n$$

where

R_n is the PSDU bit after de-whitening

RE_n is the PSDU bit at the output of the demodulator

The PN generator is defined by the schematic in Figure 17-2.

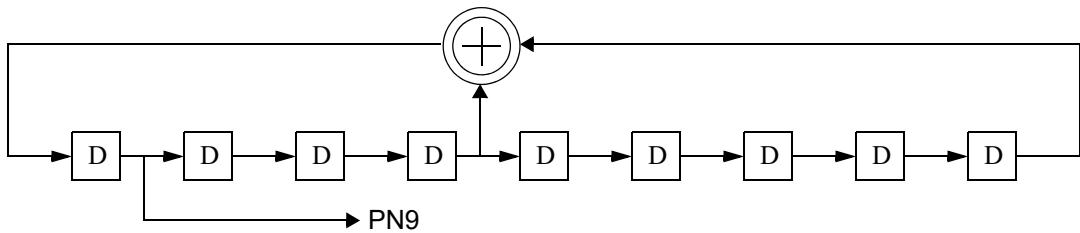


Figure 17-2—Schematic of the PN generator

The seed in the PN9 shall be all ones: “1 1 1 1 1 1 1 1 1”. The PN9 shall be reinitialized to the seed after each packet (either transmit or receive).

The PN9 generator is clocked using the seed as the starting point and enabled after the first clock cycle. For example, the first 30 bits out of the PN9, once it is enabled, would be as follows:

$$\begin{aligned} \text{PN9}_n = & 0_0 \ 0_1 \ 0_2 \ 0_3 \ 1_4 \ 1_5 \ 1_6 \ 1_7 \ 0_8 \ 1_9 \ 1_{10} \ 1_{11} \ 0_{12} \ 0_{13} \ 0_{14} \ 0_{15} \ 1_{16} \ 0_{17} \ 1_{18} \ 1_{19} \ 0_{20} \ 0_{21} \\ & 1_{22} \ 1_{23} \ 0_{24} \\ & 1_{25} \ 1_{26} \ 0_{27} \ 1_{28} \ 1_{29} \end{aligned}$$

17.2.4 GFSK modulation

The bit sequences are modulated onto the carrier using GFSK with a modulation index of one where the Gaussian filter BT is 0.5, where a bit value of one is transmitted by shifting the frequency higher than the channel center frequency and a bit value of zero is transmitted by shifting the frequency lower than the current channel center frequency.

The nominal frequency deviation shall be 50 kHz. The deviation shall be between 70% and 130% of the nominal deviation. For the sequence 0101, the deviation shall be between 70% and 110% of the nominal deviation. for the sequence 00001111, the deviation shall be between 80% and 130% of the nominal deviation.

17.3 GFSK PHY RF requirements

17.3.1 Operating frequency range

The GFSK PHY operates in the 920.8–928 MHz frequency band.

17.3.2 Transmit PSD mask

The PSD mask for the GFSK PHY is specified as follows:

- The average power measured within ± 100 kHz of the frequency 300 kHz apart from the center frequency shall be -26 dBm or less for a 1 mW device or -18 dBm or less for a 10 mW device.
- The average power measured with a 100 kHz resolution bandwidth in the frequency band from 920 MHz to 928 MHz except for the frequency band within ± 300 kHz of the carrier frequency, f_c , shall be less than -39 dBm.

17.3.3 Symbol rate

The GFSK PHY symbol rate shall be 100 ksymbol/s with an accuracy of $\pm 40 \times 10^{-6}$.

17.3.4 Receiver sensitivity

Under the conditions specified in 11.1.8, a compliant GFSK PHY device shall be capable of achieving a sensitivity of -85 dBm or better.

17.3.5 Receiver interference rejection

The minimum receiver interference rejection levels are given in Table 17-1. The adjacent channel is one on either side of the desired channel that is closest in frequency to the desired channel, and the alternate channel is one more removed from the adjacent channel. For example, when channel 15 is the desired channel, channel 14 and channel 16 are the adjacent channels, and channel 13 and channel 17 are the alternate channels.

Table 17-1—Minimum receiver interference rejection requirements for GFSK PHY

Adjacent channel rejection	Alternate channel rejection
0 dB	24 dB

The adjacent channel rejection shall be measured as follows: the desired signal shall be a compliant GFSK PHY signal, as defined by 17.2, of pseudo-random data. The desired signal is input to the receiver at a level 3 dB greater than the maximum allowed receiver sensitivity given in 17.3.4.

In either the adjacent or the alternate channel, a compliant signal, as defined by 17.2, is input at the level specified in Table 17-1 relative to the desired signal. The test shall be performed for only one interfering signal at a time. The receiver shall meet the error rate criteria defined in 11.1.8 under these conditions.

17.3.6 TX-to-RX turnaround time

The GFSK PHY shall have a TX-to-RX turnaround time as defined in 11.2.2.

17.3.7 RX-to-TX turnaround time

The GFSK PHY shall have an RX-to-TX turnaround time as defined in 11.2.3.

17.3.8 Transmit center frequency tolerance

The GFSK PHY transmit center frequency tolerance shall be $\pm 40 \times 10^{-6}$ maximum.

17.3.9 Transmit power

The GFSK PHY shall be capable of transmitting at a power level of at least -3 dBm.

17.3.10 Receiver maximum input level of desired signal

The GFSK PHY shall have a receiver maximum input level greater than or equal to -20 dBm using the measurement defined in 11.2.5.

17.3.11 Receiver ED

The GFSK PHY shall provide the receiver ED measurement as described in 11.2.6.

17.3.12 LQI

The GFSK PHY shall provide the LQI measurement as described in 11.2.7.

18. MSK PHY

18.1 PPDU formats

18.1.1 Overview

The MSK PHY shall use the PPDU formats described in 13.1, except that the Preamble field is 32 symbols (4 octets) and the bits in each octet shall be “10101010”. In addition, when implementing the 2000 kb/s data rate, the PHR field is formatted either as illustrated in Figure 18-1 or Figure 18-2, depending on the value of the Extended PHR field defined in 18.1.3.

Bits: 0–6	7
Frame Length LSB	Extended PHR

Figure 18-1—Format of PHR with Extended PHR field set to zero for 2000 kb/s data rate

Bits: 0–6	7	8–11	12–15
Frame Length LSB	Extended PHR	Frame Length MSB	Reserved

Figure 18-2—Format of PHR with Extended PHR field set to one for 2000 kb/s data rate

18.1.2 Frame Length LSB field

The Frame Length LSB field specifies the seven least significant bits of the frame length. The frame length is defined as the total number of octets contained in the PSDU (i.e., PHY payload).

18.1.3 Extended PHR field

The Extended PHR field determines the presence of the Frame Length MSB field described in 18.1.4. When the Extended PHR field is set to zero, the PHR shall be formatted as shown in Figure 18-1. When the Extended PHR field is set to one, the PHR shall be formatted as shown in Figure 18-2. The value of the Extended PHR field shall be selected by the transmitting MAC in an implementation-dependent manner, consistent with the requirement that frames having a frame length greater than 127 octets shall have the Extended PHR field set to one.

This field also indicates the length of the FCS, as described in 7.2.11. Devices that implement the 2000 kb/s data rate shall be capable of supporting the reception of both FCS lengths.

18.1.4 Frame Length MSB field

The Frame Length MSB field, when present, specifies the four most significant bits of the frame length defined in 18.1.2. As an example, a length of 497 is encoded with the Frame Length MSB field set to 1100, and the Frame Length LSB field set to 100 0111.

18.2 Data rate

All available data rates for the 433 MHz and 2450 MHz bands are shown in Table 18-1. When operating in the 433 MHz band, the mandatory data rate of the MSK PHY shall be 250 kb/s; all other data rates are optional.

Table 18-1—Data rates for MSK PHY

DataRate as used in MCPS-DATA primitives	Data rate (kb/s)	Band (MHz)
1	31.25	433
2	100	433
3	250	433 or 2450
4	2000	2450

The optional data rates for the 433 MHz band are not available on all channels. Table 18-2 shows the allowed data rates for the 433 MHz channels and their associated channel numbers.

Table 18-2—Data rate channel map

Data rate (kb/s)	Channel
31.25	0 to 14
100	1, 4, 7, 10, 13
250	2, 7, 12

18.3 Multi-PHY functionality

A transmitting device may send a Multi-PHY IE, as described in 10.26.3.4, including which PHYs are supported. If a device detects a different modulation or data rate being used on the channel, a higher layer may decide, e.g., to change the modulation and/or data rate or move the receiving device to another channel.

18.4 SFD for the MSK PHY

The SFD for the MSK PHY shall contain the value given in Table 18-3. The SFD is transmitted starting from the leftmost bit (b0).

Table 18-3—Value of the SFD field for the MSK PHY

SFD (b0–b15)
1110 0110 1101 0000

18.5 MSK modulation

18.5.1 Reference modulator diagram

The functional block diagram in Figure 18-3 is provided as a reference for specifying the MSK PHY modulation. It should be noted the preamble is not included in the whitening scheme.

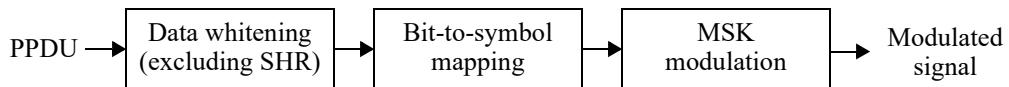


Figure 18-3—MSK functional block diagram

18.5.2 Data whitening

Data whitening for the MSK PHY shall use the procedure described in 17.2.3.

18.5.3 Bit-to-symbol mapping

The bit rate and symbol rate are equal. The mapping of bits to frequency shall be as described in Table 18-4.

Table 18-4—Bit to frequency mapping

Bit	Frequency
0	$f_c - \Delta f$
1	$f_c + \Delta f$

In Table 18-4, f_c is the channel center frequency, as defined in Table 11-10, Table 11-11, and Table 11-12. Δf is defined as follows:

$$\Delta f = \frac{1}{4 \times T_s}$$

where T_s is the symbol duration.

18.5.4 Signal modulation

When implementing the 2000 kb/s data rate, the bit sequences are modulated onto the carrier using GMSK modulation for which the Gaussian filter BT is 0.5. The MSK modulation of all other band and data rate combinations shall be FSK with modulation index $h = 0.5$.

As shown in Figure 18-4, MSK modulation has two possible frequencies over any symbol interval, which differ in frequency as follows:

$$f_2 - f_1 = \frac{1}{2T_s}$$

This is the smallest frequency difference that allows two signals to be orthogonal.

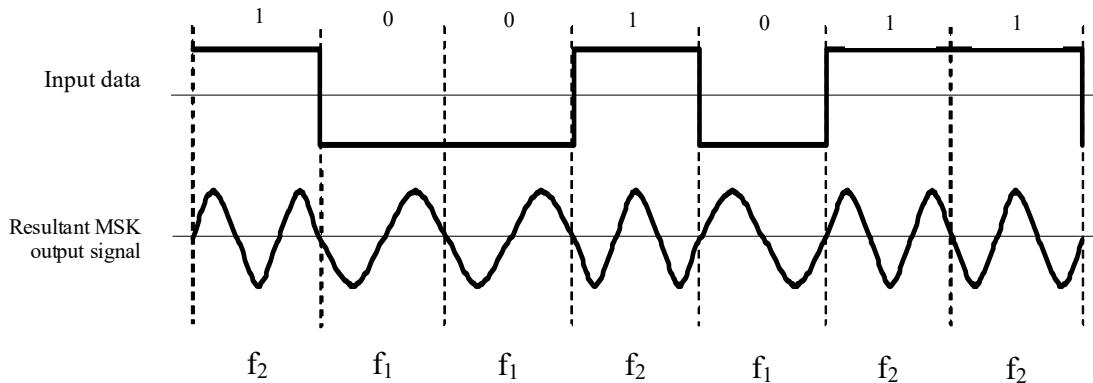


Figure 18-4—Example signal using MSK modulation in the time domain

18.6 MSK PHY requirements

18.6.1 Operating frequency range

The MSK PHY specifies the following two optional frequency bands:

- 433.05 MHz to 434.79 MHz
- 2400 MHz to 2483 MHz

18.6.2 Transmit PSD mask

The PSD mask for the MSK PHY is shown in Table 18-5.

The transmitted spectral products shall be less than the limits specified in Table 18-5. For both relative and absolute limits, average spectral power shall be measured using a 100 kHz resolution bandwidth. For the relative limit, the reference level shall be the highest average spectral power measured within a given range of the carrier frequency. The given range is ± 100 kHz for the data rate of 31.25 kb/s, ± 300 kHz for 100 kb/s, ± 600 kHz for 250 kb/s, and ± 1 MHz for 2000 kb/s.

Table 18-5—MSK PHY transmit PSD limit

Frequency band	Data rate	Frequency	Relative limit	Absolute limit
433 MHz	31.25 kb/s	$ f - f_c > 200$ kHz	-20 dB	-20 dBm
	100 kb/s	$ f - f_c > 600$ kHz	-20 dB	-20 dBm
	250 kb/s	$ f - f_c > 1.2$ MHz	-20 dB	-20 dBm
2450 MHz	250 kb/s	$ f - f_c > 1.2$ MHz	-20 dB	-20 dBm
	2000 kb/s	$ f - f_c > 3.5$ MHz	-20 dB	-30 dBm

18.6.3 Symbol rate

The transmitted symbol rate for the 433 MHz band shall be 31.25 ksymbol/s, 100 ksymbol/s, or 250 ksymbol/s with an accuracy of $\pm 300 \times 10^{-6}$.

The transmitted symbol rate for the 2450 MHz band shall be either 250 ksymbol/s with an accuracy of $\pm 300 \times 10^{-6}$ or 2000 ksymbol/s with an accuracy of $\pm 40 \times 10^{-6}$.

18.6.4 Transmit center frequency tolerance

The MSK PHY shall have a transmit center frequency tolerance of $\pm 40 \times 10^{-6}$.

18.6.5 Transmit power

The MSK PHY in the 433 MHz band shall be capable of transmitting at a power level of at least -3 dBm.

The MSK PHY in the 2450 MHz band shall be capable of transmitting at a power level of at least -13 dBm.

18.6.6 Receiver maximum input level of desired signal

The MSK PHY shall have a receiver maximum input level greater than or equal to -20 dBm using the measurement as described in 11.1.8.

18.6.7 Modulation frequency deviation tolerance

Modulation frequency tolerance is measured as a percentage of maximum frequency deviation Δf .

Modulation frequency deviation shall be constrained within $\pm 30\%$ of maximum frequency deviation Δf as defined in 18.5.3.

18.6.8 Zero crossing tolerance

All zero crossings shall be constrained within $\pm 12.5\%$ of symbol time.

19. LRP UWB PHY specification

19.1 Overview

The LRP UWB PHY is a physical layer based on band-limited impulse-radio. It operates at various low PRF. Ten frequency channels are available with center frequencies from 6489.6 MHz to 9945.6 MHz and various bandwidths. The LRP UWB PHY provides both RDEV and ERDEV functionality. The LRP-ERDEV supports authenticated ranging using distance bounding protocols.

The LRP UWB PHY uses different schemes to modulate the short UWB pulses: On-off keying (OOK) is used for RDEVs, whereas pulsed binary frequency shift keying (PBFSK) modulation and pulse position modulation (PPM) and a combination thereof are used primarily for ERDEVs, depending on the mode. The various data rates are supported through the use of a variable number of pulses per symbol, variable pulse rate or M-PPM as used for the optional enhanced payload capacity (EPC) mode, where M indicates the number of pulse positions and takes values 8, 16, or 32. Symbols are composed of one or more active bursts of UWB pulses. An optional variable pulse repetition period (PRP) provides reduced co-interference between separate networks.

The LRP UWB PHY defines the following operation modes:

- *Base mode*, for base data rate of 1 Mb/s
- *Extended mode*, for moderate data rate but improved sensitivity
- *Long-range mode*, for best sensitivity
- *Dual-frequency mode*, for shortest frames and reduced power consumption
- *Extended dual-frequency mode*, for improved sensitivity
- *Dual-frequency mode with EPC*, for higher data rates

The mandatory modes for the LRP-ERDEV are dual-frequency mode and extended dual-frequency mode for both receiver and transmitter, while all other modes are optional.

For devices that are not LRP-ERDEV, base and extended modes shall be implemented in the receiver and concurrently operational, while all other transmit and receive modes are optional.

The PHY has different characteristics depending on its operation mode. These characteristics are defined for each mode separately as shown in Table 19-1.

Table 19-1—Signaling modes and data rates for LRP UWB PHY

Mode	Modulation	PRF (MHz)	Pulses per symbol	Data rate	<i>phyLrpUwbSignaling</i> PIB attribute value	DataRate used in MCPS-DATA primitives
Long-range mode	PPM	2.0	32	31.25 kb/s	1	1
Extended mode	OOK	1.0	4	250 kb/s	2	2
Base mode	OOK	1.0	1	1 Mb/s	3	3
Dual-frequency modes	PBFSK	1.0	1	1 Mb/s	4	4
	PBFSK	2.0	1	2 Mb/s	5	5
	PBFSK	4.0	1	4 Mb/s	6	6

Table 19-1—Signaling modes and data rates for LRP UWB PHY (continued)

Mode	Modulation	PRF (MHz)	Pulses per symbol	Data rate	<i>phyLrpUwbSignaling</i> PIB attribute value	DataRate used in MCPS-DATA primitives
Extended dual-frequency modes	PBFSK	1.0	4	250 kb/s	7	7
	PBFSK	2.0	4	500 kb/s	8	8
	PBFSK	4.0	4	1 Mb/s	9	9
Dual-frequency modes with EPC	PBFSK-8PPM	1.0	1/3	3 Mb/s	10	10
	PBFSK-16PPM	1.0	1/4	4 Mb/s	11	11
	PBFSK-32PPM	1.0	1/5	5 Mb/s	12	12
	PBFSK-8PPM	2.0	1/3	6 Mb/s	13	13
	PBFSK-16PPM	2.0	1/4	8 Mb/s	14	14
	PBFSK-32PPM	2.0	1/5	10 Mb/s	15	15

19.2 LRP UWB PHY symbol structure

19.2.1 Overview

In base mode, the LRP UWB PHY symbol consists of presence/absence of pulses in 1 MHz PRF sequence.

In extended mode, the LRP UWB PHY symbol consists of presence/absence of pulses in 1 MHz PRF sequence generated by convolution code with octal generators (5,7,7,7).

In long-range mode, the LRP UWB PHY symbol consists of Manchester-encoded groups of 64 pulses (32 on, 32 off) in 2 MHz PRF sequence.

In dual-frequency modes, the LRP UWB PHY symbol consists of the presence of pulses at either one of the center frequencies defined in Table 19-5, transmitted at nominal PRF values of 1 MHz, 2 MHz, or 4 MHz.

Extended dual-frequency modes have four pulses per symbol generated by convolution with octal generators (5,7,7,7).

The EPC mode that may optionally be employed with dual-frequency modes, and that applies only to the PSDU field of the PPDU, consists of the presence of pulses at either one of the center frequencies defined in Table 19-5, transmitted at rates of 1 MHz or 2 MHz PRF with modulation of the pulse position within the symbol with 8-PPM, 16-PPM, or 32-PPM. For the EPC mode, the PBFSK modulation corresponds to a stream of alternate frequencies.

The LRP-ERDEV may optionally include a variable PRP feature as described in 19.2.6.

19.2.2 Base mode LRP UWB PHY symbol structure

19.2.2.1 Overview

In the base mode of the LRP UWB modulation scheme, each symbol carries one bit of information. The base mode operates at 1 chip per symbol and with a PRF of 1 MHz, so the symbol time T_{dsym} is 1 μ s and the chip time T_{CHIP} is also 1 μ s. Binary data values 0 and 1 are encoded as per Table 19-2. The data rate is thus 1 Mb/s. The pulse duration T_{PULSE} is much shorter than the symbol time. The pulse is nominally sent in the center of the chip and symbol period T_{dsym} as shown in Figure 19-1.

Table 19-2—Base mode LRP UWB symbol encoding

Binary value being encoded	Transmitted signal
0	No energy is transmitted during the 1 μ s symbol time
1	A single pulse is transmitted during the 1 μ s symbol time

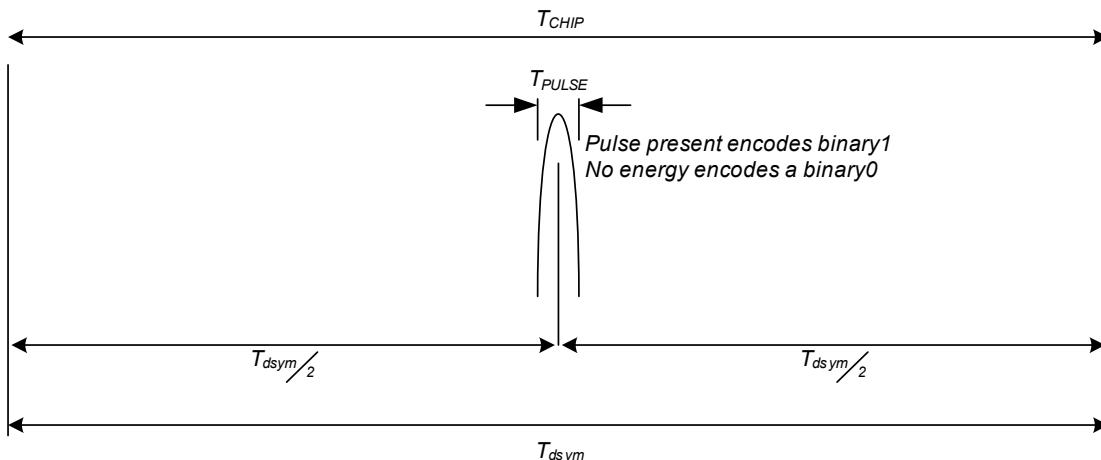


Figure 19-1—Base mode LRP UWB PHY symbol structure

19.2.2.2 Base mode LRP UWB PHY PSDU synchronization signal

During the base mode PSDU transmission, after every 128 symbols of user data, the PHY inserts four chips of binary 1. This provides enough information to the receiver to retain synchronization when the user data is all zeros. These four chips/symbols are removed in the PHY and not decoded as user data.

19.2.3 Extended mode LRP UWB PHY symbol structure

19.2.3.1 Overview

In the extended mode of the LRP UWB modulation scheme, each symbol consists of four chips generated by a rate one-quarter convolutional code using octal generators 5,7,7,7 for $k = 3$, as shown in Figure 19-2.

The extended mode receiver may employ a relatively simple Viterbi decoder with hard or soft decisions to make use of the coding gain afforded by the transmitter convolution code.

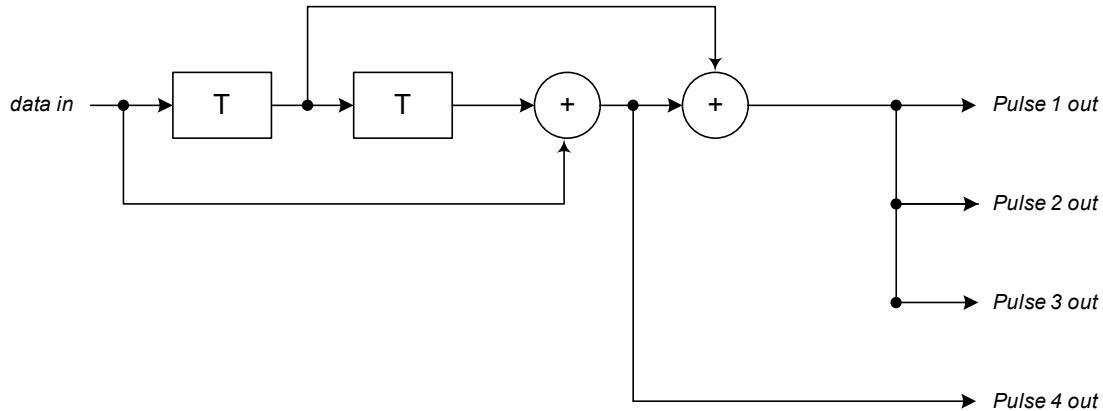


Figure 19-2—Extended mode LRP UWB PHY transmitter convolution code

Extended mode employs a PRF of 1 MHz with a rate 1/4 code giving a symbol time of 4 μ s. The data rate is thus 250 kb/s. The pulses are nominally centered within the chip periods as shown in Figure 19-3. These four pulses are transmitted in order with pulse 1 transmitted first. The individual pulses shown are present, depending on whether the pulse out value is binary 1 or binary 0 as indicated in Table 19-3.

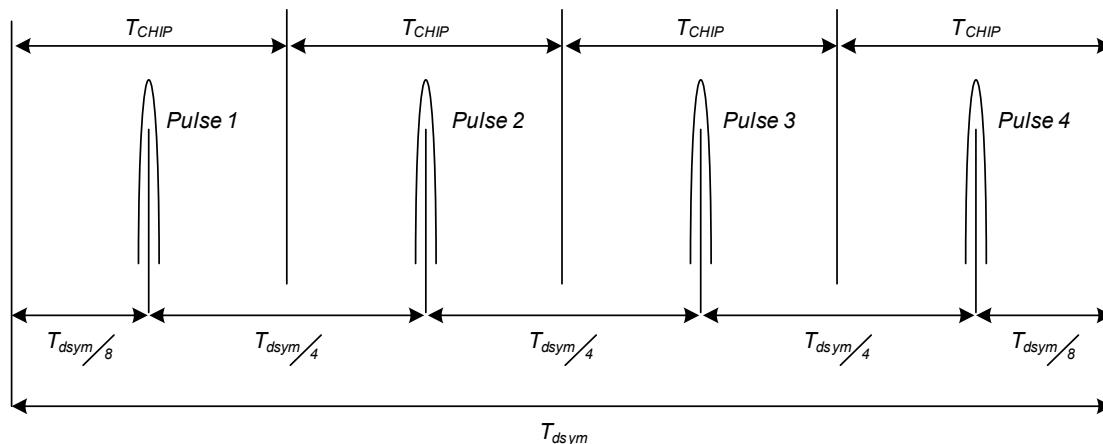


Figure 19-3—Extended mode LRP UWB PHY symbol structure

Table 19-3—Extended mode LRP UWB pulse to chip encoding

Pulse out value	Transmitted chip
0	No energy is transmitted during this chip time
1	A pulse is transmitted during this chip time

19.2.3.2 Extended mode LRP UWB PHY PSDU synchronization signal

During the extended mode PSDU transmission, after every 32 symbols of user data, which is (128 chips), the PHY inserts four chips of “1” pulse. This provides enough information to the receiver to retain synchronization when the encoded output pulses are “0” pulses (i.e., no transmitted energy). These four chips (1 symbol of pulses) are removed in the PHY before the received pulse (Viterbi) decoding.

19.2.4 Long-range mode LRP UWB PHY symbol structure

19.2.4.1 Overview

In the long-range mode of the LRP UWB modulation scheme, each symbol encodes one bit using 64 chips at a chipping rate of 2 MHz PRF, with Manchester encoding as given in per Table 19-4. The data rate is thus 31.25 kb/s. Figure 19-4 shows this diagrammatically. When a pulse is present, it is nominally centered within the chip period.

Table 19-4—Long-range mode LRP UWB symbol encoding

Binary value being encoded	Transmitted signal
0	The symbol period is 32 μ s. No energy is transmitted during first 16 μ s, and then in the second 16 μ s, 32 pulses are transmitted.
1	The symbol period is 32 μ s. In the first 16 μ s, 32 pulses are transmitted, and then no energy is transmitted during second 16 μ s.

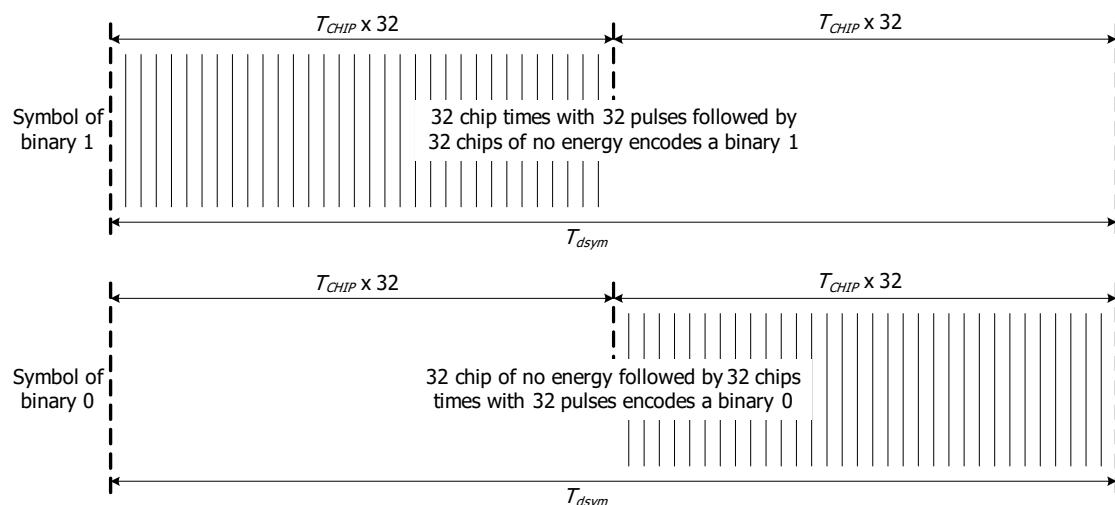


Figure 19-4—Long-range mode LRP UWB PHY symbol structure

19.2.4.2 Long-range mode LRP UWB PHY PSDU synchronization signal

No additional synchronization measures are needed in long-range mode since its Manchester encoding scheme provides sufficient pulses.

19.2.5 Dual-frequency LRP UWB PHY symbol structure

19.2.5.1 General

In the dual-frequency modulation scheme(s), each symbol is modulated by means of PBFSK modulation. The PBFSK modulation carrying binary values zero and one encodes them by shifting the center frequency of the UWB pulse carrier as described in Table 19-5.

Table 19-5—PBFSK pulse frequency encoding

Binary value being encoded	Transmitted pulse center frequency
0	The RF carrier of the pulse is shifted by $-f_{\text{dev}}$
1	The RF carrier of the pulse is shifted by $+f_{\text{dev}}$

The value of parameter f_{dev} is specified in 19.2.5.2.

19.2.5.2 Frequency deviation for dual-frequency modes

The modulation for the LRP-ERDEV PHY is PBFSK with pulse shaping to generate the UWB pulse envelope.

The frequency deviation, f_{dev} , shall be 153.6 MHz.

19.2.5.3 Dual-frequency and extended dual-frequency (without EPC)

In non-EPC modes, the dual-frequency modulation operates at one or four chips (pulses) per symbol with a PRF of 1 MHz, 2 MHz, or 4 MHz. Four chips per symbol is defined as the extended version of the dual-frequency modes at the different PRFs.

The pulse is nominally sent in the center of the chip period T_{CHIP} as shown in Figure 19-1 for the base mode and Figure 19-3 for the extended mode, except that for the dual-frequency modulation (in contrast to the OOK modulation) pulses are present for both binary values as per the encoding specified in Table 19-5.

19.2.5.4 Dual-frequency modes synchronization

No additional synchronization measures are needed for dual-frequency modes since the PBFSK modulation transmits pulses in every symbol.

19.2.6 Variable pulse repetition period (PRP)

Optionally, seven additional PRP/PRF values are provided for each nominal PRF, for network separation and interference reduction. For each nominal PRF these are specified by the parameter k_{PRP} . To calculate the PRP, the base chipping period of 1 μ s is divided into 128 equal duration slots, that is of 7.8125 ns. The 1 μ s period corresponds to 128, 64, and 32 time slots for nominal PRF of 1 MHz, 2 MHz, and 4 MHz, respectively (nominal chipping periods of 1 μ s, 0.5 μ s, and 0.25 μ s, respectively). The modified PRP are obtained by subtracting the time shift of $k_{\text{PRP}} \times 7.8125$ ns from the nominal chipping periods, where k_{PRP} has values in the range of 0 to 7, as per Table 19-6, where $T_{\text{CHIP}} = T_{\text{dsym}}$. The first row of Table 19-6 contains the nominal PRFs.

The selection of k_{PRP} is achieved using the *phyLrpUwbPrp* attribute.

Table 19-6—Variable PRP parameters for each nominal PRF

PRP Mode k_{PRP}	$T_{\text{CHIP}} (\mu\text{s})$	PRF (MHz)	$T_{\text{CHIP}} (\mu\text{s})$	PRF (MHz)	$T_{\text{CHIP}} (\mu\text{s})$	PRF (MHz)
0	1	1	0.5	2	0.25	4
1	0.9921875	1.007874016	0.4921875	2.031746032	0.2421875	4.129032258
2	0.984375	1.015873016	0.484375	2.064516129	0.234375	4.266666667
3	0.9765625	1.024	0.4765625	2.098360656	0.2265625	4.413793103
4	0.96875	1.032258065	0.46875	2.133333333	0.21875	4.571428571
5	0.9609375	1.040650407	0.4609375	2.169491525	0.2109375	4.740740741
6	0.953125	1.049180328	0.453125	2.206896552	0.203125	4.923076923
7	0.9453125	1.05785124	0.4453125	2.245614035	0.1953125	5.12

19.3 LRP UWB SHR

19.3.1 General

The SHR consists of two components: the LRP UWB SHR preamble and SFD.

19.3.2 LRP UWB SHR preamble

19.3.2.1 LRP UWB base mode SHR preamble

The LRP UWB base mode SHR preamble consists of a continuous stream of pulses at the base mode PRF of 1 MHz, with the number of pulses being between 16 and 128 for devices that are not LRP-ERDEV, or between 16 and 256 for LRP-ERDEV, as specified by the `UwbPreambleSymbolRepetitions` parameter of the `MCPS-DATA`, `MCPS-RANGING-VERIFIER`, and `MCPS-RANGING-PROVER` primitives.

19.3.2.2 RP UWB extended mode SHR preamble

The LRP UWB extended mode SHR preamble consists of a continuous stream of pulses at the extended mode PRF of 1 MHz, with a length between 16 and 256.

19.3.2.3 LRP UWB long-range mode SHR preamble

The LRP UWB long-range mode SHR preamble consists of three segments, which are transmitted in turn, as follows:

- a) A continuous stream of pulses at the long-range mode PRF of 2 MHz, with a length between 1024 and 8192 pulses.
- b) The following pulse/no-pulse sequence, transmitted at a PRF of 2 MHz where “-” represents “no pulse”, and “P” represents a pulse:

$$\text{--- P - P --- P P P - P}$$
- c) A series of between 16 and 64 “1” symbols, transmitted as per the long-range mode PHY symbol structure defined in 19.2.4.

19.3.2.4 LRP UWB dual-frequency mode SHR preamble

The SHR preamble for all LRP UWB dual-frequency modes consists of a continuous stream of pulses with alternate binary values [0, 1, 0, 1, ..., 0, 1, 0, 1] using the encoding frequencies as specified in Table 19-5, and transmitted at the nominal PRF of 1 MHz, 2 MHz, or 4 MHz as specified in Table 19-1, or the PRF according to the specification in Table 19-6 when variable PRP is being employed. The number of pulses in the preamble shall be between 16 and 256.

19.3.3 LRP UWB SHR SFD

19.3.3.1 SFD for devices that are not LRP-ERDEV

The SFD for the LRP UWB PHY is common to all modes and shall be formatted as illustrated in Figure 19-5. The modulation encoding for the SFD shall be 1 pulse per bit for both the base and extended modes. The modulation encoding for the long-range mode shall be Manchester encoded with 64 chips per bit as specified for long-range mode.

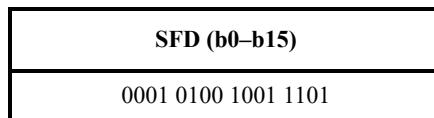


Figure 19-5—Value of the SFD field for LRP UWB PHY

The SFD is transmitted starting from the leftmost bit (b0).

19.3.3.2 Additional SFD for LRP-ERDEV

The SFD for the LRP-ERDEV UWB PHY can be of length 32, 64, or 128 pulse periods selected by the *phyLrpUwbSfdSelector* attribute from the sequences specified in Table 19-7. In all cases transmission order is b0 (leftmost and topmost) first in time. The length 128 SFD selected by *phyLrpUwbSfdSelector* value of 7 shall be the default for the LRP-ERDEV.

Table 19-7—SFD sequences for the LRP-ERDEV

SFD length	<i>phyLrpUwbSfdSelector</i> attribute value	Selected SFD sequence (b0 to b32/b64/b128)
32	0	1000 0100 1011 0011 1110 0011 0111 0100
	1	0001 1011 1100 0010 1011 1001 0110 1100
64	2	0001 0111 0010 1100 1000 0101 0111 1100 0011 1100 1110 1110 0010 1010 1100 0110
	3	0011 0101 1111 0011 0010 1011 0100 1111 1000 1100 1001 0111 0000 0000 1010 1110
	4	0111 0111 1101 1110 1101 0001 1010 1100 1011 0111 1001 0000 1001 0010 0000 1000
	5	1111 0011 1000 0101 0010 0100 0110 1010 1100 0001 1001 1111 1011 0111 0100 0100
	6	1011 0001 1010 1000 1101 1110 1000 1001 1111 1010 1001 1000 0010 0101 1110 0010

Table 19-7—SFD sequences for the LRP-ERDEV (continued)

SFD length	<i>phyLrpUwbSfdSelector</i> attribute value	Selected SFD sequence (b0 to b32/b64/b128)
128	7	1000 0001 0001 0011 0001 0111 0101 1011 0000 0110 0110 1010 0111 0011 1101 1010 0001 0101 0111 1101 0010 1000 1101 1100 0111 1111 0000 1110 1111 0010 1100 1000
	8	1100 1110 0011 1010 0011 1010 0000 1011 0110 0010 0101 0000 1001 0100 1100 0001 0010 0101 0101 1110 1100 0001 0111 1110 1000 1001 1110 0001 0001 0011 1001 0001
	9	0101 1000 1001 0010 0000 1000 0001 0110 0001 0001 1101 1101 0000 1100 1101 0000 1101 0001 1000 1111 1011 1010 0000 1001 0111 1001 0100 1101 0101 1100 1011 1001

19.4 LRP UWB PHR

19.4.1 General

This is defined in symbols and is therefore common to base, extended, and long-range modes, with the exception of the encoding type (bits 0–2). The encoding type is defined in symbols for long-range mode and as pulses for basic and extended mode.

The PHY Header field of the LRP UWB modulation shall be formatted as illustrated in Table 19-6.

Bits: 0–2	3	4–9	10–16	17	18–20	21
Encoding Type	Header Extension	SECDED	Frame Length	Reserved	LEIP Length	LEIP Position

Figure 19-6—PHR format for LRP UWB PHY

19.4.2 Encoding Type field

Long-range mode is specified (and detected) by its own unique symbol mapping, defined in 19.2.4, and the use of a 2 MHz PRF. In long-range mode the Encoding Type field of the PHR is given by Table 19-8.

Table 19-8—PHR Encoding Type field in long-range mode

Encoding Type value b0–b2	Meaning
000	Each symbol encodes 1 bit. Each symbol consists of 64 chips and uses Manchester encoding. This encoding is defined in 19.2.4.
001 to 111	Reserved

In base mode and extended mode where the PHR is sent with a chip rate of 1 MHz, the Encoding Type field of the PHR is given by Table 19-9. These three bits are encoded as per 19.2.2. Only two values are legal, 000 and 111. This allows a receiver to use all three bits in a voting scheme to determine whether it should

switch to using extended mode decoding for the remainder of the PHR and the PSDU or should continue decoding the PHR and PSDU in base mode.

Table 19-9—PHR Encoding Type field base mode and extended mode

Encoding Type value b0–b2	Meaning
000	This value indicates the operating mode is base mode. All remaining bits in the frame continue to be encoded as per 19.2.2.
111	This value indicates the operating mode is extended mode. All bits in the remaining fields of the PHR and PSDU are encoded as per 19.2.3.
001 to 110	ILLEGAL—These values can never be legally used. The receiver may use all three bits of the two legal values 000 and 111 in a voting scheme to decide which is actually present.

19.4.3 Header Extension field

The PHR Header Extension bit shall be set to zero upon transmission. If a PPDU is received with the PHR Header Extension bit set, the device shall discard the PPDU.

19.4.4 SECDED field

The SECDED field is a simple Hamming block code that enables the correction of a single error and the detection of two errors at the receiver. The SECDED field is computed as follows:

$$b9 = \text{XOR} (b21, b18, b19, b20, b17)$$

$$b8 = \text{XOR} (b10, b11, b12, b13, b14, b15, b16)$$

$$b7 = \text{XOR} (b1, b2, b3, b13, b14, b15, b16, b20, b17)$$

$$b6 = \text{XOR} (b0, b2, b3, b11, b12, b15, b16, b18, b19)$$

$$b5 = \text{XOR} (b0, b1, b3, b10, b12, b14, b16, b21, b19, b17)$$

$$b4 = \text{XOR} (b0, \dots, b3, b5, \dots, b21)$$

19.4.5 Frame Length field

The Frame Length field is an unsigned integer that shall be set to the length of the PSDU in octets. The Frame Length field shall be transmitted MSB first.

19.4.6 Location enhancing information postamble (LEIP) Length field

This gives the length of the location enhancing information postamble (LEIP) in pulses. The meaning of this field is defined in Table 19-10.

Table 19-10—PHR LEIP Length field meaning

LEIP Length field value (b18 b19 b20)	LEIP sequence length
000	Not present
001	16 pulses
010	64 pulses
011	128 pulses
100	192 pulses
101	256 pulses
110	512 pulses
111	1024 pulses

19.4.7 LEIP Position field

The LEIP Position field specifies the position of the optional LEIP sequence. The LEIP Position field only applies if the LEIP Length field indicates that the LEIP sequence length is non-zero, in which case the meaning of this bit is then as defined in Table 19-11. When the LEIP Length field indicates that the LEIP sequence is not present, then the LEIP Position field is reserved.

Table 19-11—PHR LEIP Position bit meaning

LEIP Position field value	Meaning
0	The LEIP is delayed
1	The LEIP is not delayed

When the LEIP sequence is delayed, it is delayed by $aLeipDelayTime$ from start of SFD. The LEIP then starts on the first chipping interval after the delay. Where the PSDU is of sufficient length that it has not ended by this time, then the LEIP is deferred to start in the chipping interval immediately following the final chipping interval being used for the PSDU.

When the LEIP is not delayed, the LEIP starts in the chipping interval immediately following the final chipping interval being used for the PSDU.

19.5 LRP UWB PSDU

19.5.1 General

In base mode the PSDU is encoded as per 19.2.2; in extended mode the PSDU is encoded as per 19.2.3; and in long-range mode the PSDU is encoded as per 19.2.4.

In non-EPC dual-frequency modes the PSDU is encoded as per 19.2.5.3, and in dual-frequency mode using EPC the PSDU is encoded as per 19.5.2.

19.5.2 PSDU in enhanced payload capacity (EPC) mode

The EPC mode provides higher data rates in the PSDU of the LRP UWB PHY. This mode is only available in (non-extended) dual-frequency mode of operation for PRFs of 1 MHz and 2 MHz. Limiting to lower PRFs allows the insertion of a sufficiently long guard interval to accommodate high RF multipath environments. When using EPC modes, the dual-frequency modulation is carrying 3, 4, or 5 bits per pulse.

This mode uses PBFSK with M-ary PPM modulation scheme only during the PSDU portion of the frame.

The symbol has two parts:

- The PPM “active” part of duration $T_{\text{PPM}} = (M - 1) \times d_{\text{PPM}}$
- A guard interval of duration $T_{\text{guard}} = T_{\text{dsym}} - T_{\text{PPM}}$

where M represents the number of pulse positions of M-ary PPM and $M = 8, 16$, or 32 , (for 3, 4, or 5 bits per pulse, respectively), and d_{PPM} is the time interval between possible pulse positions within the active part of the symbol.

The earliest of the M pulse positions of PPM is located in the center of the chip and symbol period T_{dsym} as shown in Figure 19-7. The time interval d_{PPM} is selected according to the modulation as specified in Table 19-12. The total guard time (T_{guard}) is the sum of the time before (T_{guard1}) and after (T_{guard2}) the active portion of the symbol T_{PPM} . With the two PRF of 1 MHz and 2 MHz and the time intervals of 7.8125 ns (1/64th of the PRF) and 15.625 ns (1/32nd of the PRF), the PSDU provides data rates from 3 Mb/s to 10 Mb/s with various guard intervals to accommodate different channel conditions.

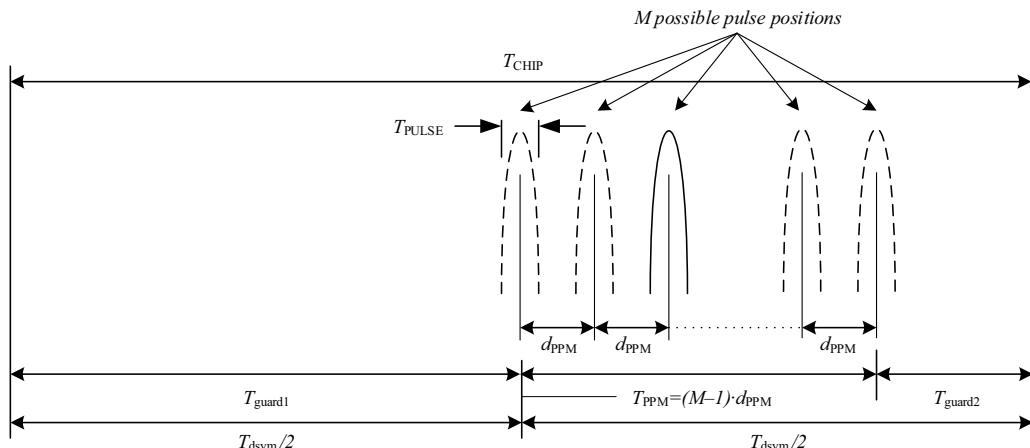


Figure 19-7—Dual-Frequency EPC mode symbol structure

Table 19-12—Modulation parameters in EPC modes

Modulation	PRF (MHz)	Pulses per bit	Data rate (Mb/s)	d_{PPM} (ns)	T_{dsym} (μs)	T_{PPM} (ns)	T_{guard} (ns)
PBFSK-8PPM	1.0	1/3	3.0	15.625	1.0	109.375	890.625
PBFSK-16PPM	1.0	1/4	4.0	15.625	1.0	234.375	765.625
PBFSK-32PPM	1.0	1/5	5.0	7.8125	1.0	242.1875	703.125

Table 19-12—Modulation parameters in EPC modes (*continued*)

Modulation	PRF (MHz)	Pulses per bit	Data rate (Mb/s)	d_{PPM} (ns)	T_{dsym} (μs)	T_{PPM} (ns)	T_{guard} (ns)
PBFSK-8PPM	2.0	1/3	6.0	15.625	0.5	109.375	445.3125
PBFSK-16PPM	2.0	1/4	8.0	15.625	0.5	234.375	382.8125
PBFSK-32PPM	2.0	1/5	10.0	7.8125	0.5	242.1875	257.8125

When using EPC in conjunction with the variable PRP described in 19.2.6, the appropriate T_{dsym} is taken from Table 19-6 and used to calculate guard times.

The example below computes the resulting PPM active time T_{PPM} and the guard time T_{guard} when using the modified PRP $k_{\text{PRP}} = 7$ in EPC mode, resulting in a chip and symbol period of $T_{\text{dsym}|k_{\text{PRP}=7}} = 945.3125$ ns (derived from the mode with nominal T_{dsym} of 1 μs) and targeting a peak data rate of approximately 5 Mb/s by using PBFSK-32PPM, (i.e., where $M=32$):

$$T_{\text{PPM}} = (M - 1) \times d_{\text{PPM}} = 31 \times 7.8125 \text{ ns} = 242.1875 \text{ ns}$$

$$T_{\text{guard}} = T_{\text{dsym}|k_{\text{PRP}=7}} - T_{\text{PPM}} = 945.3125 \text{ ns} - 242.1875 \text{ ns} = 703.125 \text{ ns}$$

$$T_{\text{guard}} = \frac{T_{\text{dsym}}}{2}$$

$$T_{\text{guard2}} = T_{\text{guard}} - T_{\text{guard1}}$$

19.6 LRP UWB location enhancing information postamble

The LEIP consists of a sequence of UWB pulses. The PRF of the LEIP pulse sequence is as follows:

- 1 MHz in the LRP UWB base and extended modes
- 2 MHz in the long-range mode
- Various PRF for the LRP-ERDEV using the same format as described in 19.3.2.4 for the SHR, the number of pulses being defined in the DataRequestRangingDescriptor

Information in the PHY header, as defined in 19.4, indicates whether or not the LEIP is appended to a transmitted packet.

If the information in the PHY header indicates that the LEIP is appended to the transmitted packet, further information in the PHY header indicates when the first LEIP pulse occurs. It occurs either:

- Immediately after the end of the PSDU, or
- *aLeipDelayTime* after the start of the SHR SFD

The length of the LEIP (in pulses, at the appropriate rate) is defined in Table 19-10 by the PHR LEIP length field.

19.7 LRP UWB transmitter specification

19.7.1 Pulse shape

The LRP UWB PHY shall employ an impulse transmitter that instantaneously produces an ultra wideband frequency response. There are no constraints on the specific pulse shape providing that the pulse shall comply with the Transmit PSD Mask defined in 19.7.3.

For dual-frequency modes using the PBFSK modulation, the normalized PSD of the modulated frequency response shall comply with the transmit PSD mask specified in 19.7.3 for the chosen operating band. Normalized PSD means PSD being such that the largest measured bin value is subtracted from all measured bins. Figure 19-8 is an example of LRP-ERDEV dual frequency mode spectrum fitting into the PSD mask for channel band 6 (as specified in Table 19-14).

To help with interoperability in ranging scenarios, it is mandatory for the LRP-ERDEV to use transmitted pulse shapes with minimum precursor energy as depicted in the left-hand plot of Figure 16-23. The pulse shall monotonically rise to the main peak amplitude. For LRP-ERDEV in dual frequency mode, the 1% to 99% rise time of the transmitted pulse envelope shall be $2.7 \text{ ns} \pm 0.35 \text{ ns}$.

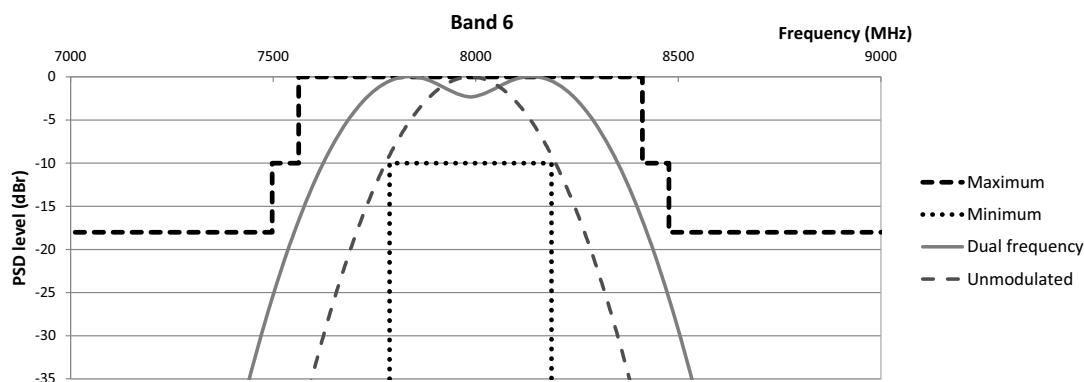


Figure 19-8—Example of PSD mask spectral compliance for dual-frequency modes

19.7.2 Pulse timing

The transmission time of any individual pulse shall not drift more than 11 ns from its nominal transmission time during a 128 symbol period over the specified operating temperature range of the device.

For an LRP-ERDEV, the transmission time of any individual pulse shall not drift more than 2 ns from its nominal transmission time during 128 pulse periods transmitted at the lowest PRF of 1 MHz over the specified operating temperature range of the device.

In order to avoid long sequences of zeros driving the need for high-quality clocks, the symbol structure in the base and extended modes includes a periodic sync marker as described in 19.2.2.2 and 19.2.3.2. No additional sync marker is required in the long-range mode.

19.7.3 Transmit PSD mask

The transmitter shall be capable of operating with a PSD contained by at least one of four PSD masks defined in Table 19-13 and shown in Figure 19-9. The LRP-ERDEV shall additionally be capable of supporting at least one of the channels listed in Table 19-14, where for each channel supported the transmitter shall be capable of operating with the respective PSD defined in Table 19-14 and Figure 19-10.

The permitted spectral density is defined in dBr relative to the maximum spectral density of the signal, and shall be made using a 1 MHz resolution bandwidth and a 1 MHz video bandwidth. Additionally, the upper –10 dBr point of the transmitter PSD shall be at least 200 MHz above a nominal frequency, f_n , and the lower –10 dBr point shall be at most 200 MHz below the same nominal frequency.

Table 19-13—LRP UWB PHY PSD mask

Channel band number	f_n (MHz)	Frequency (MHz)	PSD limit (dBr)
0	6489.6	< 5624.32	-18
		5624.32 to 5786.56	-10
		5786.56 to 7192.64	0
		7192.64 to 7354.88	-10
		> 7354.88	-18
1	6988.8	< 6090.24	-18
		6090.24 to 6165.12	-10
		6165.12 to 8311.68	0
		8311.68 to 8386.56	-10
		> 8386.56	-18
2	7987.2	< 6922.24	-18
		6922.24 to 7121.92	-10
		7121.92 to 8852.48	0
		8852.48 to 9052.16	-10
		> 9052.16	-18
3	8486.4	< 7587.84	-18
		7587.84 to 7662.72	-10
		7662.72 to 9809.28	0
		9809.28 to 9884.16	-10
		> 9884.16	-18

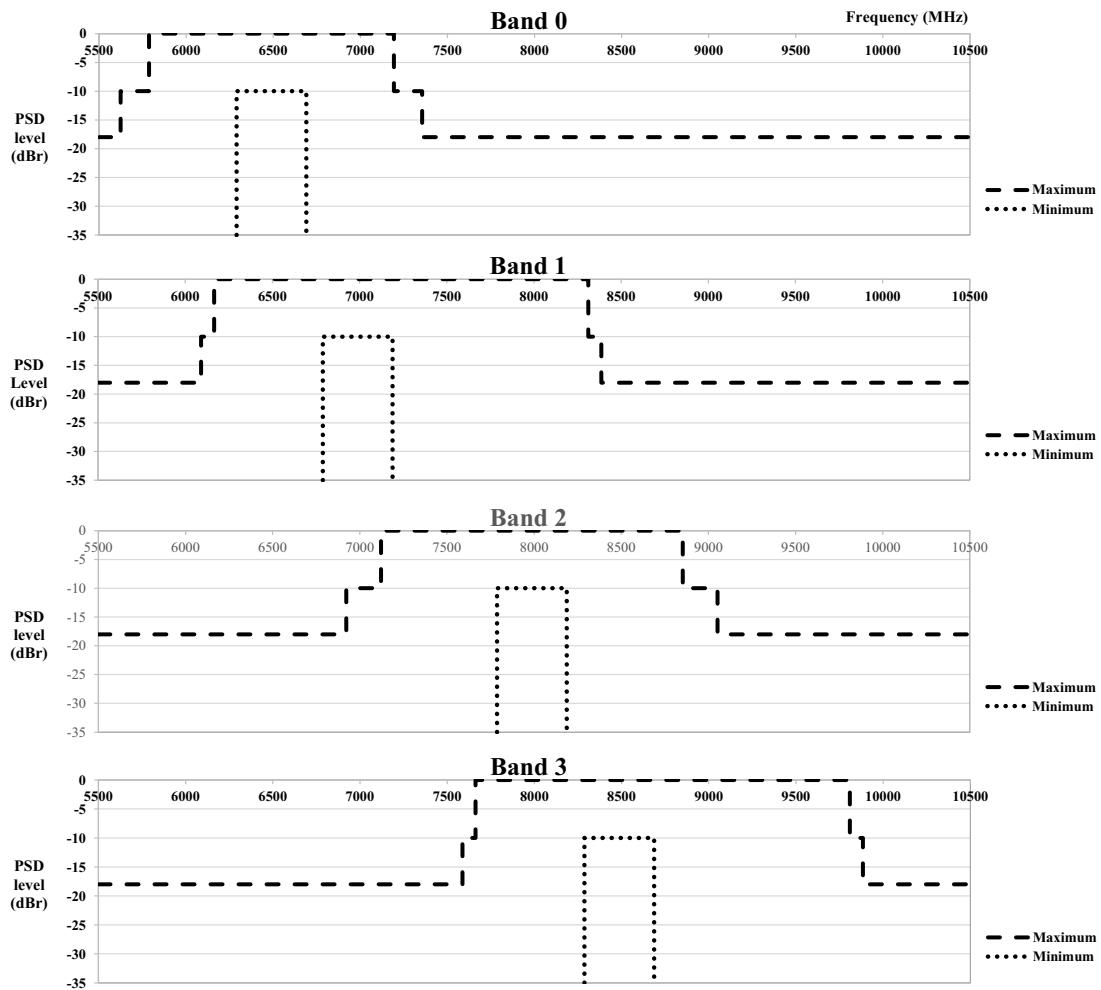


Figure 19-9—LRP-ERDEV LRP UWB PHY PSD masks

Table 19-14—LRP-ERDEV channelized PSD mask

Channel band number	f_n (MHz)	Frequency (MHz)	PSD limit (dBr)
4	6681.6	< 6192.0	-18
		6192.0 to 6257.3	-10
		6257.3 to 7105.9	0
		7105.9 to 7171.2	-10
		> 7171.2	-18
5	7334.4	< 6844.8	-18
		6844.8 to 6910.1	-10
		6910.1 to 7758.7	0
		7758.7 to 7824.0	-10
		> 7824.0	-18
6	7987.2	< 7497.6	-18
		7497.6 to 7562.9	-10
		7562.9 to 8411.5	0
		8411.5 to 8476.8	-10
		> 8476.8	-18
7	8640.0	< 8150.4	-18
		8150.4 to 8215.7	-10
		8215.7 to 9064.3	0
		9064.3 to 9129.6	-10
		> 9129.6	-18
8	9292.8	< 8803.2	-18
		8803.2 to 8868.5	-10
		8868.5 to 9717.1	0
		9717.1 to 9782.4	-10
		> 9782.4	-18
9	9945.6	< 9456.0	-18
		9456.0 to 9521.3	-10
		9521.3 to 10369.9	0
		10369.9 to 10435.2	-10
		> 10435.2	-18

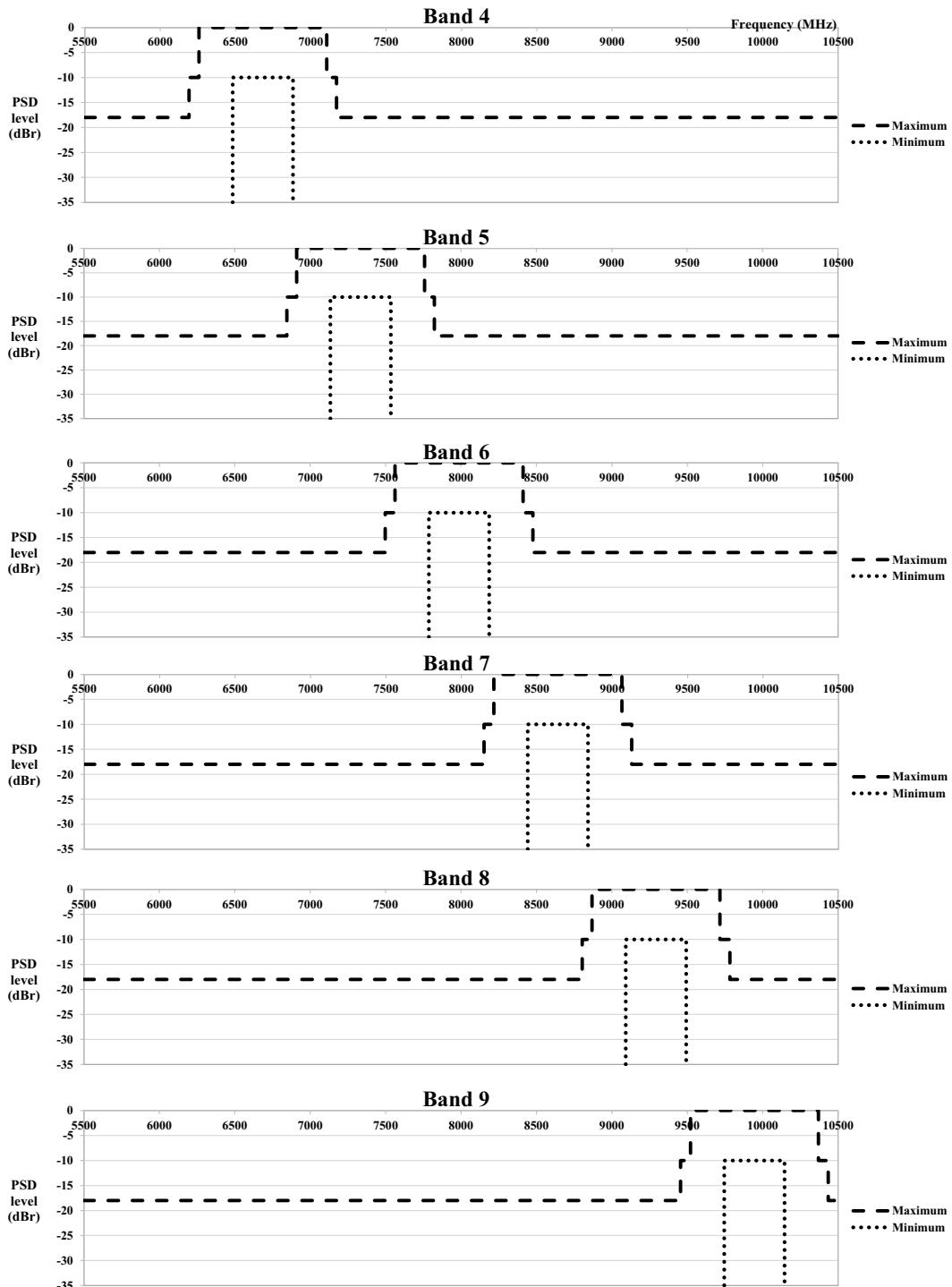


Figure 19-10—LRP-ERDEV channelized PSD masks

19.8 LRP UWB transmit and receive timing requirements

19.8.1 Fixed reply time

The receive-to-transmit reply time for a device with a *phyLrpUwbFixedReplyTimeSupported* attribute value of TRUE shall be the fixed reply time as specified in Table 19-15 selected by the *phyLrpUwbFixedReplyTime* attribute. The RSTU units are specified in 10.29.1.5 and the pulse timing accuracy for the LRP-ERDEV is specified in 19.7.2.

Table 19-15—Fixed reply times for the LRP-ERDEV

Value of the <i>phyLrpUwbFixedReplyTime</i> attribute	Selected fixed reply time (RSTU, number of base chip periods)
FRT3	3
FRT7	7
FRT15	15
FRT31	31

Assuming a nominally synchronized transmitter and receiver, a fixed reply time of FRTx corresponds to an equivalent time of FRTx + 1 between the active portion (pulses) of the last received chip and the first transmitted chip. In the example of Figure 19-11, a fixed reply time value of FRT3 defines a pulse-to-pulse fixed reply time of four RSTU.

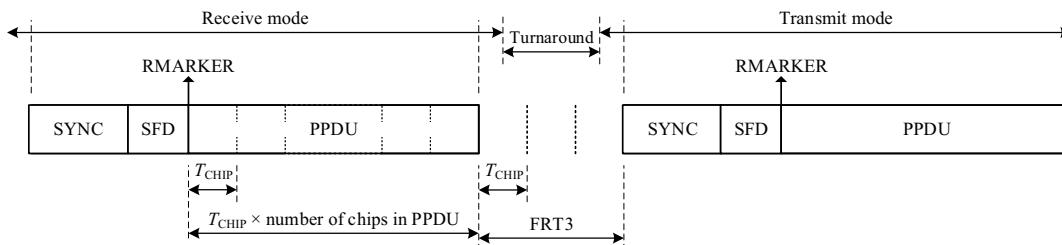


Figure 19-11—Fixed reply time as a function of FRTx parameter for LRP-ERDEV

19.8.2 Turnaround times

When the *phyLrpUwbFixedReplyTimeSupported* attribute is set to TRUE, the turnaround time for a device to be configured from receiver to transmitter mode and from transmitter to receiver mode shall be less than the fixed reply time as specified in Table 19-15 selected by the *phyLrpUwbFixedReplyTime* attribute.

20. SUN FSK PHY

20.1 Introduction

A SUN device shall support the SUN FSK PHY, allowing MPM signaling utilizing the CSM.

For the SUN FSK PHY, the symbol period used for MAC and PHY timing parameters, shown in Table 20-1, shall be the symbol period of operating mode #1 or operating mode #1a specified in Table 20-7, Table 20-8, and Table 20-9.

Table 20-1—SUN FSK symbol period used for MAC and PHY timing parameters

Frequency band (MHz)	Symbol period used for MAC and PHY timing parameters (μs)
169.400–169.475	208+1/3
450–470	104+1/6
470–510	20
779–787	20
863–870	20
865–868	20
866–869	20
870–876	20
896–901	100
901–902	100
902–928	20
902–928(alternate)	20
902–907.5 and 915–928	20
915–928	20
915–921	20
915–918	20
917–923.5	20
919–923	20
920–928	20
920.5–924.5	20
920–925	20
928–960	100
1427–1518	100
2400–2483.5	20

For the purposes of calculating the Ack frame timing required in 6.6.4, the default length of the Preamble field shall be 8 octets, and mode switch shall not be used for Ack frames.

20.2 PPDU format for SUN FSK

20.2.1 General

The SUN FSK PPDU shall support the format shown in Figure 20-1 and may support the format shown in Figure 20-2 if mode switch is enabled.



Figure 20-1—Format of the SUN FSK PPDU (without mode switch)



Figure 20-2—Format of the SUN FSK mode switch PPDU

20.2.2 SHR field format

20.2.2.1 General

The SHR field shall be formatted as illustrated in Figure 20-3.

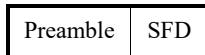


Figure 20-3—Format of the SHR

20.2.2.2 Preamble field

The Preamble field shall contain *phyFskPreambleLength* (as defined in 12.3.10) multiples of the 8-bit sequence “01010101” for 2-FSK. The Preamble field shall contain *phyFskPreambleLength* multiples of the 16-bit sequence “0111 0111 0111 0111” for 4-FSK.

20.2.2.3 SFD

The SFD for 2-FSK shall be a 2-octet sequence selected from the values shown in Table 20-2. The SFD for 4-FSK shall be a 4-octet sequence selected from the values shown in Table 20-3. Devices that do not support FEC shall support the SFD associated with uncoded format and a value of zero for the PIB attribute *phySunFskSfd*, as defined in 12.3.11; these devices may also support the SFD associated with uncoded format and a value of one for the PIB attribute *phySunFskSfd*. Devices that support FEC shall support both SFDs associated with a value of zero for the PIB attribute *phySunFskSfd*; these devices may additionally support both SFDs associated with a value of one for the PIB attribute *phySunFskSfd*.

The SFD is transmitted starting from the leftmost bit (i.e., starting with b0).

Table 20-2—SUN FSK PHY SFD values for 2-FSK

	SFD value for coded format (b0–b15)	SFD value for uncoded format (b0–b15)
<i>phySunFskSfd = 0</i>	0110 1111 0100 1110	1001 0000 0100 1110
<i>phySunFskSfd = 1</i>	0110 0011 0010 1101	0111 1010 0000 1110

Table 20-3—SUN FSK PHY SFD values for 4-FSK

	SFD value for coded format (b0–b31)	SFD value for uncoded format (b0–b31)
<i>phySunFskSfd = 0</i>	0111 1101 1111 1111 0111 0101 1111 1101	1101 0111 0101 0101 0111 0101 1111 1101
<i>phySunFskSfd = 1</i>	0111 1101 0101 1111 0101 1101 1111 0111	0111 1111 1101 1101 0101 0101 1111 1101

20.2.3 PHR field format

The format of the PHR is shown in Figure 20-4.

Bits: 0	1–2	3	4	5–15
Mode Switch	Reserved	FCS Type	Data Whitening	Frame Length

Figure 20-4—Format of the PHR for SUN FSK

The Mode Switch field shall be set to zero, indicating that the entire packet shall be transmitted at a single data rate and using a single modulation scheme.

The FCS Type field indicates the length of the FCS field described in 7.2.11 that is included in the MPDU. The FCS Type field shall be set to zero for a 4-octet FCS and shall be set to one for a 2-octet FCS.

The Data Whitening field indicates whether data whitening of the PSDU is used upon transmission. The Data Whitening field shall be set to one when data whitening is used and shall be set to zero otherwise.

The Frame Length field is an unsigned integer that shall be set to the total number of octets contained in the PSDU (prior to FEC encoding, if enabled). The Frame Length field shall be transmitted MSB first. The PHR is transmitted starting from the leftmost bit (i.e., starting with b0).

20.2.4 Mode Switch PHR

The format of the Mode Switch PHR is shown in Figure 20-5.

Bits: 0	1–2	3	4–10	11–14	15
Mode Switch	Mode Switch Parameter	New Mode FEC	New Mode	Checksum	Parity Check

Figure 20-5—Format of the Mode Switch PHR for SUN FSK

The Mode Switch field shall be set to one, indicating that a mode switch shall occur. The mode of the next PPDU transmitted (i.e., the new mode PPDU) shall be as described by the remaining fields contained in the PHR in Figure 20-5. If the new mode is SUN FSK, the new mode PPDU is the same as Figure 20-1 except that the preamble and SFD are optional. For SUN OFDM, the new mode PPDU has the same format as Figure 21-1. If the new mode is SUN O-QPSK, the new mode PPDU is the same as Figure 22-1.

The Mode Switch Parameter field is the index of the entry in the *phySunModeSwitchParameterEntries* array, as described in Table 12-12, that defines the mode switch parameters to be used, as described in Table 12-13. If the Mode Switch Parameter field indicates an unsupported entry in the *phySunModeSwitchParameterEntries* array of the receiver, the receiver shall discard the packet and remain in the present PHY mode.

The New Mode FEC field specifies whether the packet following the mode switch PPDU is transmitted using FEC. A value of zero indicates that the new mode packet is transmitted without FEC, and a value of one indicates that it is transmitted with FEC. If the new mode packet has an SFD and, therefore, packet coding information, as described in 20.3.5, the SFD shall override the value of the New Mode FEC field.

The New Mode field is formatted as shown in Figure 20-6.

Bits: 0	1–2	3–6
Page	Modulation Scheme	Mode

Figure 20-6—Format of the New Mode field

The Page field shall be set to zero to indicate SUN PHYs or set to one to indicate SUN FSK Generic PHY.

The Modulation Scheme field indicates the modulation scheme, as described in Table 20-4.

Table 20-4—Modulation Scheme field values

Field value	Description
0	SUN FSK
1	SUN OFDM
2	SUN O-QPSK
3	Additional modes

The Mode field specifies the new mode of operation. When the Page field is zero, the interpretation of the Mode field is based on the following modulation scheme:

- If the modulation scheme is SUN FSK, the Mode field is a bitmap where a bit is set to one if the operating mode given in Table 20-5 is to be used. If multiple bits are set, or all bits are clear, the mode switch header shall be ignored.
- If the modulation scheme is additional modes, the additional modes field values is specified in Table 20-6.
- If the modulation scheme is not FSK, the Mode field shall be set to zero upon transmission and ignored upon reception. The corresponding data rates are specified in the PHR of the new mode PPDU.

Table 20-5—Mode field values

Bit	Description
0	SUN FSK operating mode #1
1	SUN FSK operating mode #2
2	SUN FSK operating mode #3
3	SUN FSK operating mode #4

Table 20-6—Additional Modes field values

Mode Value	Mode description
0x0	SUN FSK operating mode #5
0x1	SUN FSK operating mode #1a
0x2	SUN FSK operating mode #1b
0x3	SUN FSK operating mode #6
0x4	SUN FSK operating mode #7
0x5	SUN FSK operating mode #8
0x6	SUN FSK operating mode #9
0x7	SUN FSK operating mode #10
0x8	SUN FSK operating mode #11
0x9	SUN FSK operating mode #12
0xA–0xF	Reserved

When the Page field is one, the new PHY mode is defined by the SUN FSK Generic PHY mechanism.

The generator polynomial for the Checksum field is a Bose Chaudhuri Hocquenghem (BCH) code. The checksum for the BCH(15,11) code is calculated as follows:

$$G(x) = 1 + x + x^4$$

The Parity Check field provides error detection for the mode switch PPDU. Its value is calculated using the first 11 bits from the PHR,(b0, b1, ... b10), using the following equation:

$$\text{Parity Check} = b0 \oplus b1 \oplus b2 \oplus b3 \oplus b4 \oplus b5 \oplus b6 \oplus b7 \oplus b8 \oplus b9 \oplus b10$$

where \oplus is modulo-2 addition (addition over GF(2)). The combination of the BCH(15,11) code and one parity bit allows for the achievement of single error correction and double error detection over the first 11 bits of the PHR.

If the receiving device receives a PHR with the Mode Switch field set to one, it first performs the BCH calculation over the first 11 bits of the PHR. If the resulting checksum is valid, and the Mode Switch field is still set to one after error correction, a parity check using the Parity Check field is performed. If the result of

the parity check is valid, the receiving device processes the mode switch and decodes the subsequent PPDU. If the result of the parity check is invalid, or if the Mode Switch field is set to zero after the error correction, the receiver terminates the receive procedure.

The Mode Switch PHR is transmitted starting from the leftmost bit (i.e., starting with b0).

20.2.5 PHY Payload field

The PHY Payload field carries the PSDU, encoded as described in 20.3.2.

20.3 Modulation and coding for SUN FSK

20.3.1 General

The modulation for the SUN FSK PHY is either a 2- or a 4-level FSK that meets the transmit spectral mask, as defined in 20.6.6.

Table 20-7 shows the modulation and channel parameters for the standard-defined PHY operating modes for the 169 MHz, 450 MHz, 470 MHz, 779 MHz, 863 MHz, 896 MHz, 901 MHz, 915 MHz, 928 MHz, 1427 MHz, and 2450 MHz bands. A device shall support operating mode #1 and may additionally support operating modes #2 and #3. For the 866 MHz band, a device shall support operating modes #1 and #2 and may additionally support operating mode #3.

Table 20-7—SUN FSK modulation and channel parameters^a

Band designation (MHz)	Parameter	Operating mode #1	Operating mode #2	Operating mode #3
169	Data rate (kb/s)	4.8	2.4	9.6
	Modulation	2-FSK	2-FSK	4-FSK
	Modulation index	0.5	2.0	0.33
	Channel spacing (kHz)	12.5	12.5	12.5
450	Data rate (kb/s)	9.6	4.8	—
	Modulation	4-FSK	2-FSK	—
	Modulation index	0.33	1.0	—
	Channel spacing (kHz)	12.5	12.5	—
470	Data rate (kb/s)	50	100	150
	Modulation	2-FSK	2-FSK	2-FSK
	Modulation index	1.0	0.5	0.5
	Channel spacing (kHz)	200	200	200
779	Data rate (kb/s)	50	100	200
	Modulation	2-FSK	2-FSK	4-FSK
	Modulation index	1.0	1.0	0.33
	Channel spacing (kHz)	200	400	400
863	Data rate (kb/s)	50	100	150
	Modulation	2-FSK	2-FSK	2-FSK
	Modulation index	0.5	0.5	0.5
	Channel spacing (kHz)	100	200	200

Table 20-7—SUN FSK modulation and channel parameters^a (continued)

Band designation (MHz)	Parameter	Operating mode #1	Operating mode #2	Operating mode #3
866	Data rate (kb/s)	50	100	150
	Modulation	2-FSK	2-FSK	2-FSK
	Modulation index	0.5	0.5	0.5
	Channel spacing (kHz)	100	200	200
896	Data rate (kb/s)	10	20	40
	Modulation	2-FSK	2-FSK	2-FSK
	Modulation index	0.5	0.5	0.5
	Channel spacing (kHz)	12.5	12.5	12.5
901	Data rate (kb/s)	10	20	40
	Modulation	2-FSK	2-FSK	2-FSK
	Modulation index	0.5	0.5	0.5
	Channel spacing (kHz)	12.5	12.5	12.5
915	Data rate (kb/s)	50	150	200
	Modulation	2-FSK	2-FSK	2-FSK
	Modulation index	1.0	0.5	0.5
	Channel spacing (kHz)	200	400	400
917	Data rate (kb/s)	50	150	200
	Modulation	2-FSK	2-FSK	2-FSK
	Modulation index	1.0	0.5	0.5
	Channel spacing (kHz)	200	400	400
928 ^b	Data rate (kb/s)	10	20	40
	Modulation	2-FSK	2-FSK	2-FSK
	Modulation index	0.5	0.5	0.5
	Channel spacing (kHz)	25	25	25
1427 ^b	Data rate (kb/s)	10	20	40
	Modulation	2-FSK	2-FSK	2-FSK
	Modulation index	0.5	0.5	0.5
	Channel spacing (kHz)	25	25	25
2450	Data rate (kb/s)	50	150	200
	Modulation	2-FSK	2-FSK	2-FSK
	Modulation index	1.0	0.5	0.5
	Channel spacing (kHz)	200	400	400

^a Data rates shown are over-the-air data rates (the data rate transmitted over the air regardless of whether the FEC is enabled).

^b Noncontiguous.

Table 20-8 shows the modulation and channel parameters for the standard-defined PHY operating modes for the 867 MHz, 870 MHz, 915 MHz-a, 915 MHz-b, 915 MHz-c, 915 MHz-d, 915 MHz-e, 919 MHz, 920 MHz, 920 MHz-a, and 920 MHz-b bands. For these bands, a device shall support both operating modes #1 and #2 and may additionally support operating modes #3, #4, and #5.

Table 20-8—SUN FSK modulation and channel parameters for additional sub-GHz bands^a

Band designation (MHz)	Parameter	Operating mode #1	Operating mode #2	Operating mode #3	Operating mode #4	Operating mode #5
867	Data rate (kb/s)	50	100	150	200	300
	Modulation	2-FSK	2-FSK	2-FSK	2-FSK	2-FSK
	Modulation index	0.5	0.5	0.5	0.5	0.5
	Channel spacing (kHz)	100	200	200	400	400
870	Data rate (kb/s)	50	100	150	—	—
	Modulation	2-FSK	2-FSK	2-FSK	—	—
	Modulation index	0.5	0.5	0.5	—	—
	Channel spacing (kHz)	100	200	200	—	—
915-a	Data rate (kb/s)	50	100	150	200	300
	Modulation	2-FSK	2-FSK	2-FSK	2-FSK	2-FSK
	Modulation index	1.0	0.5	0.5	0.5	0.5
	Channel spacing (kHz)	200	200	200	400	400
915-b	Data rate (kb/s)	50	100	150	200	300
	Modulation	2-FSK	2-FSK	2-FSK	2-FSK	2-FSK
	Modulation index	1.0	0.5	0.5	0.5	0.5
	Channel spacing (kHz)	200	200	200	400	400
915-c	Data rate (kb/s)	50	100	150	200	300
	Modulation	2-FSK	2-FSK	2-FSK	2-FSK	2-FSK
	Modulation index	1.0	0.5	0.5	0.5	0.5
	Channel spacing (kHz)	200	200	200	400	400
915-d	Data rate (kb/s)	50	100	150	200	300
	Modulation	2-FSK	2-FSK	2-FSK	2-FSK	2-FSK
	Modulation index	1.0	0.5	0.5	0.5	0.5
	Channel spacing (kHz)	200	200	200	400	400
915-e	Data rate (kb/s)	50	100	150	200	300
	Modulation	2-FSK	2-FSK	2-FSK	2-FSK	2-FSK
	Modulation index	1.0	0.5	0.5	0.5	0.5
	Channel spacing (kHz)	200	200	200	400	400

Table 20-8—SUN FSK modulation and channel parameters for additional sub-GHz bands^a (continued)

Band designation (MHz)	Parameter	Operating mode #1	Operating mode #2	Operating mode #3	Operating mode #4	Operating mode #5
919	Data rate (kb/s)	50	100	150	200	300
	Modulation	2-FSK	2-FSK	2-FSK	2-FSK	2-FSK
	Modulation index	1.0	0.5	0.5	0.5	0.5
	Channel spacing (kHz)	200	200	200	400	400
920	Data rate (kb/s)	50	100	200	400	400
	Modulation	2-FSK	2-FSK	2-FSK	4-FSK	4-FSK
	Modulation index	1.0	1.0	1.0	0.33	0.33
	Channel spacing (kHz) ^b	200	400	600	600	400
920-a	Data rate (kb/s)	50	100	150	—	—
	Modulation	2-FSK	2-FSK	2-FSK	—	—
	Modulation index	1.0	0.5	0.5	—	—
	Channel spacing (kHz)	200	200	200	—	—
920-b	Data rate (kb/s)	50	100	150	200	300
	Modulation	2-FSK	2-FSK	2-FSK	2-FSK	2-FSK
	Modulation index	1.0	0.5	0.5	0.5	0.5
	Channel spacing (kHz)	200	200	200	400	400

^a Data rates shown are over-the-air data rates (the data rate transmitted over the air regardless of whether the FEC is enabled).

^b Channel spacing shows bundling of 200 kHz channels.

Frequency bands 470 MHz, 780 MHz, 863 MHz, 866 MHz, 867 MHz, 870 MHz, 915 MHz, 915 MHz-a, 915 MHz-b, 915 MHz-c, 915 MHz-d, 915 MHz-e, 917 MHz, 919 MHz, 920 MHz, 920 MHz-a, and 920 MHz-b may additionally support operating modes #1a and #1b as specified in Table 20-9.

Table 20-9—Additional SUN FSK modulation and channel parameters

Parameters	Operating mode #1a	Operating mode #1b
Data rate (kb/s)	10	20
Modulation	2-FSK	2-FSK
Modulation index	1.0	1.0
Channel spacing (kHz)	50	100

Frequency band 920 MHz may additionally support operating modes #6, #7, #8, #9, #10, #11, and #12 as specified in Table 20-10.

Table 20-10—Additional SUN FSK modulation and channel parameters

Band designation (MHz)	Parameter	Operating mode #6	Operating mode #7	Operating mode #8	Operating mode #9	Operating mode #10	Operating mode #11	Operating mode #12
920	Data rate (kb/s)	150	300	300	400	600	600	800
	Modulation ^a	2-FSK	2-FSK	2-FSK	2-FSK	2-FSK	4-FSK	4-FSK
	Modulation index	0.5	0.5	0.5	0.5	0.4	0.5	0.33
	Channel Spacing (kHz)	400	400	600	1000 ^b	1000 ^b	100 ^b	1000 ^b

^a GFSK with the Gaussian filter value (BT) of 0.5.

^b Usage of channels and channel separation is defined in 11.1.3.9.

In addition to the standard-defined PHY operating modes, the SUN FSK PHY may support a SUN FSK Generic PHY mechanism, which enables the use of a broader set of data rates and PHY parameters to describe a PHY mode. The set of PHY operating mode parameters is defined by the SUN FSK Generic PHY IE, as defined in 10.14.3.2.

20.3.2 Reference modulator

The functional block diagram of the reference modulator as shown in Figure 20-7 is provided as a reference for specifying the SUN FSK PHY data flow processing functions. Each bit shall be processed using the bit order rules defined in 20.2.

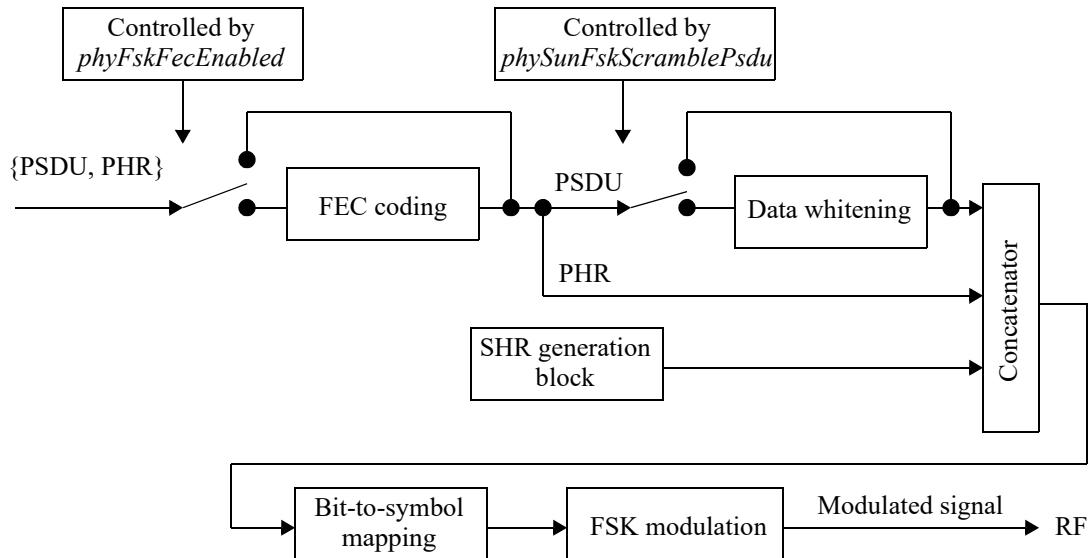


Figure 20-7—SUN FSK reference modulator

When FEC is enabled, the PHR and PSDU shall be processed for coding as a single block of data, as described in 20.3.5. When data whitening is enabled, the scrambling shall be only applied over the PSDU, as described in 20.4.

All fields in the PPDU shall use the same symbol rate and modulation order, unless otherwise specified elsewhere in this standard.

20.3.3 Bit-to-symbol mapping

The nominal frequency deviation, Δf , shall be as follows:

$$\Delta f = \left(\frac{\text{symbol rate} \times \text{modulation index}}{2} \right)$$

The symbol encoding for 2-FSK is shown in Table 20-11 and for 4-FSK in Table 20-12, where the frequency deviation, f_{dev} , is equal to Δf for 2-FSK and is equal to $3 \times \Delta f$ for 4-FSK. For 4-FSK modulation, two bits shall be mapped to four frequency deviation levels for the PHR and PHY Payload field. The SHR shall be encoded in the lowest ($-f_{\text{dev}}$) and the highest ($+f_{\text{dev}}$) frequency deviations. The symbol rate shall be the same for the entire PPDU.

Table 20-11—SUN 2-FSK symbol encoding

Symbol (binary)	Frequency deviation
0	$-f_{\text{dev}}$
1	$+f_{\text{dev}}$

Table 20-12—SUN 4-FSK symbol encoding

Symbol (binary)	Frequency deviation
01	$-f_{\text{dev}}$
00	$-f_{\text{dev}} / 3$
10	$+f_{\text{dev}} / 3$
11	$+f_{\text{dev}}$

20.3.4 Modulation quality

20.3.4.1 General

Modulation quality shall be measured by observing the frequency deviation tolerance and the zero crossing tolerance of the eye diagram caused by a PN9 sequence of length 511 bits.

20.3.4.2 Frequency deviation tolerance

Modulation frequency tolerance is measured as a percentage of the frequency deviation, f_{dev} , dictated by the modulation index. In the case of 2-FSK, the measured frequency deviation, f , at $T_{\text{s(recovered)}} / 2$ shall be constrained to the range $70\% f_{\text{dev}} < |f| < 130\% f_{\text{dev}}$, as shown in Figure 20-8, where $T_{\text{s(recovered)}}$ is the recovered symbol time, corrected for the symbol timing offset. In the case of 4-FSK, the measured frequency deviation, f , at $T_{\text{s(recovered)}} / 2$ shall be constrained to the range $8\% f_{\text{dev}} < |f| < 58\% f_{\text{dev}}$ for the inner levels and $75\% f_{\text{dev}} < |f| < 125\% f_{\text{dev}}$ for the outer levels, as shown in Figure 20-9.

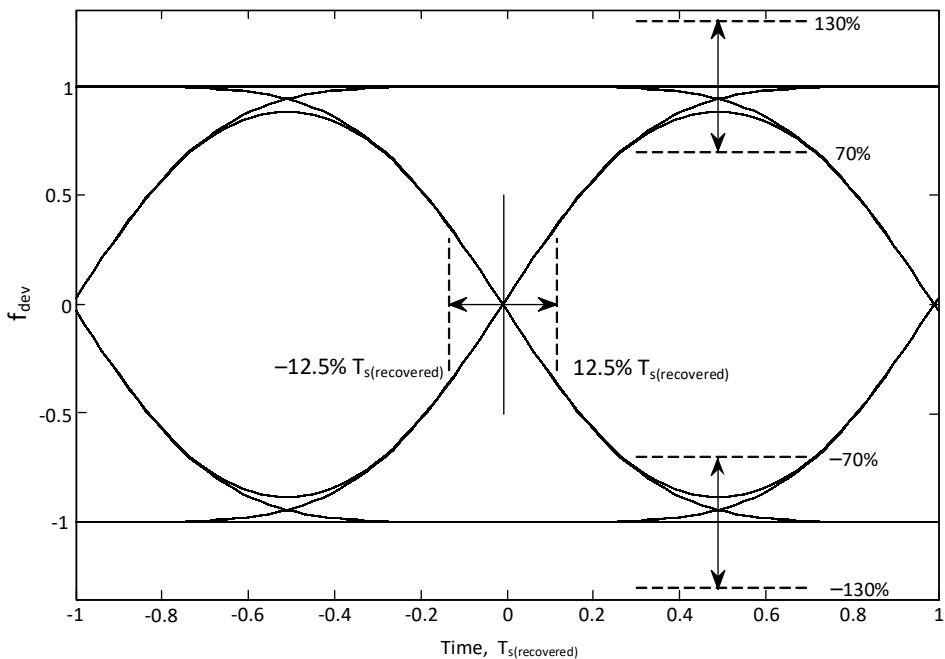


Figure 20-8—Eye diagram for 2-FSK

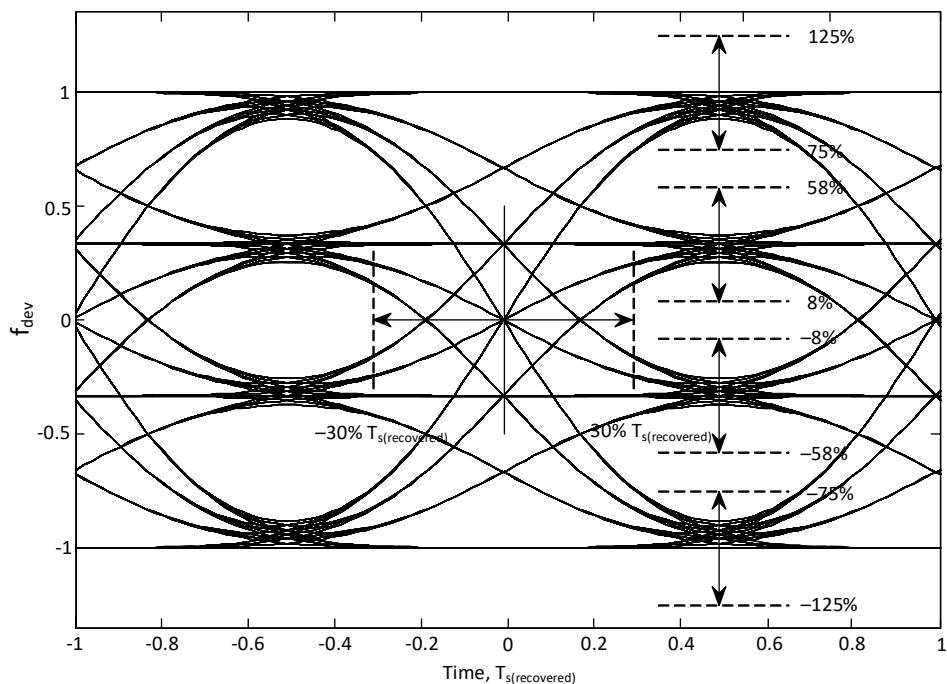


Figure 20-9—Eye diagram for 4-FSK

20.3.4.3 Zero crossing tolerance

In the case of 2-FSK, the excursions for the zero crossings for all trajectories of the eye diagram shall be constrained to within $\pm 12.5\%$ rms of the symbol time T_s , as shown in Figure 20-8. In the case of 4-FSK, the excursions for the zero crossings for all trajectories of the eye diagram shall be constrained to within $\pm 30\%$ of the symbol time T_s , as shown in Figure 20-9.

20.3.5 FEC

FEC is optional. If the SFD indicates that FEC is used, as described in Table 20-2, then the FEC is applied to the PHR and PSDU as a single block of data.

Two types of FEC may be applied: RSC or NRNSC. The use of RSC or NRNSC coding shall be controlled by the PIB attribute *phyFskFecScheme*, as defined in 12.3.10.

When the SFD value indicates a coded packet, FEC shall be employed on the PHR and PSDU bits, applying either a 1/2-rate systematic or nonsystematic convolution coding with constraint length $K = 4$, and using the following two generator polynomials:

$$G_0(x) = 1 + x + x^2 + x^3$$

$$G_1(x) = 1 + x^2 + x^3$$

The total number of bits to be encoded, N , is obtained by summing up the size of the PHR (L_{PHR}), the length of the PSDU (L_{PSDU} is equal to the content of the Frame Length field in Figure 20-4), the number of tail bits (L_{TAIL}), and the number of padding bits (L_{PAD}). N shall be computed as follows:

$$N = L_{\text{PHR}} + L_{\text{PSDU}} + L_{\text{TAIL}} + L_{\text{PAD}}$$

NOTE—The value of L_{PSDU} is zero in the case of a mode switch packet.

Immediately after encoding the PHR and PSDU, a termination sequence with length $L_{\text{TAIL}} = 3$ bits shall be inserted into the encoder, as shown in Figure 20-10. The tail bits are required to return the encoder to the zero state.

PHR	PSDU	Tail bits
-----	------	-----------

Figure 20-10—Data block extension with tail bits prior to coding

The value of the tail bits are dependent on the coding scheme and shall be set as shown in Table 20-13.

Table 20-13—Tail bit pattern for the RSC and NRNSC encoders

Memory state (M_0-M_2)	Tail bits	
	RSC (b0 b1 b2)	NRNSC (b0 b1 b2)
000	000	000
001	100	000
010	110	000
011	010	000

Table 20-13—Tail bit pattern for the RSC and NRNSC encoders (continued)

100	111	000
101	011	000
110	001	000
111	101	000

When interleaving is used in conjunction with convolutional coding, a padding sequence of L_{PAD} bits shall be further inserted into the encoder immediately after the tail bits. The padding bits are required to fill up the last interleaver buffer completely, as described in 20.3.6. L_{PAD} shall be computed as follows:

$$L_{PAD} = 5, \text{ when } \frac{L_{PHR} + L_{PSDU}}{8} \text{ is odd}$$

$$L_{PAD} = 13, \text{ when } \frac{L_{PHR} + L_{PSDU}}{8} \text{ is even}$$

Padding bit patterns should not contain a long series of 1s or 0s. Figure 20-11 and Figure 20-12 illustrate examples of such patterns.

PHR	PSDU	Tail bits	5-bit padding pattern: 01011
-----	------	-----------	------------------------------

Figure 20-11—An example of extension with padding bits prior to encoding, when $(L_{PHR} + L_{PSDU})/8$ is odd

PHR	PSDU	Tail bits	13-bit padding pattern: 0 1011 0000 1011
-----	------	-----------	--

Figure 20-12—An example of extension with padding bits prior to encoding, when $(L_{PHR} + L_{PSDU})/8$ is even

The RSC encoder is shown in Figure 20-13, and the NRNSC encoder is shown in Figure 20-14.

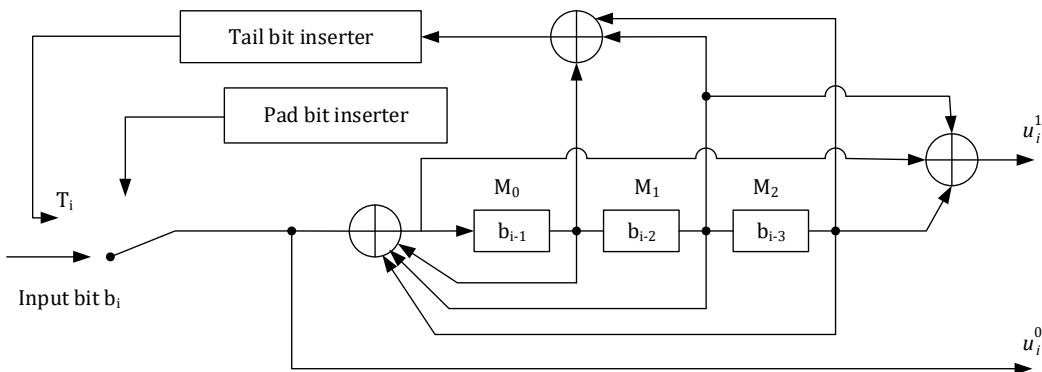


Figure 20-13—The recursive and systematic code (RSC) encoder

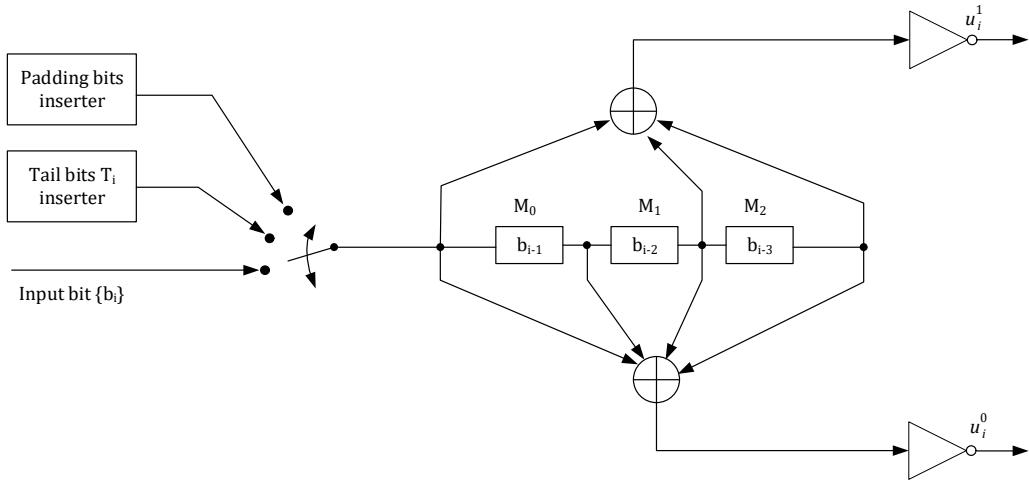


Figure 20-14—Non-recursive and non-systematic code (NRNSC) encoder

For an input sequence of bits with length N , $B = \{b_i, i \in [0, 1, 2, \dots, N-1]\}$, the i th input bit shall be represented as b_i and be fed into memory state M_0 , M_1 , and M_2 in that order. The tail bits T_i and the pad bits shall be inserted once the encoding of PHR and PSDU is complete. The output sequence S also comprises N code-symbols.

$$S = \{s(0), s(1), s(2), \dots, s(N-1)\} = \{u_0^1, u_0^0, \dots, u_i^1, u_i^0, u_{i+1}^1, u_{i+1}^0, \dots, u_{N-1}^1, u_{N-1}^0\}$$

Each code-symbol is denoted by $s(i) = \{u_i^1, u_i^0\}$, for all $i = 0, \dots, N-1$, where $s(i)$ is the i th output code-symbol due to the i th input bit and u_i^1 and u_i^0 indicate the first and second output bits of the convolutional encoder, respectively. The code-symbol $s(i)$ shall precede the code-symbol $s(i+1)$, and the code bit u_i^1 shall precede the code bit u_i^0 .

For the RSC encoder, the first and the second output bits of the encoder shall be generated in the following way:

$$u_i^1 = b_i \oplus (b_{i-1} \oplus b_{i-2} \oplus b_{i-3}) \oplus b_{i-2} \oplus b_{i-3}$$

$$u_i^0 = b_i$$

where \oplus stands for modulo-2 addition.

For the NRNSC encoder, the first and the second output bits of the encoder shall be generated in the following way:

$$u_i^1 = \overline{b_i \oplus b_{i-2} \oplus b_{i-3}}$$

$$u_i^0 = \overline{b_i \oplus b_{i-1} \oplus b_{i-2} \oplus b_{i-3}}$$

where the overline indicates the complement of the modulo-2 addition.

20.3.6 Code-symbol interleaving

Interleaving of code bits shall be employed in conjunction with NRNSC coding, in order to improve robustness against burst errors and to break correlation of consecutive bits. Interleaving may also be employed with RSC coding. In the case of RSC coding, the use of the interleaver is controlled by the PIB attribute *phyFskFecInterleavingRsc*, as defined in 12.3.10. No interleaving shall be employed if FEC is not enabled. The interleaver is defined by a permutation of code-symbols, where each permuted element contains exactly one code-symbol, i.e., a pair of two bits, as described in 20.3.5. The process of interleaving is illustrated in Figure 20-15.

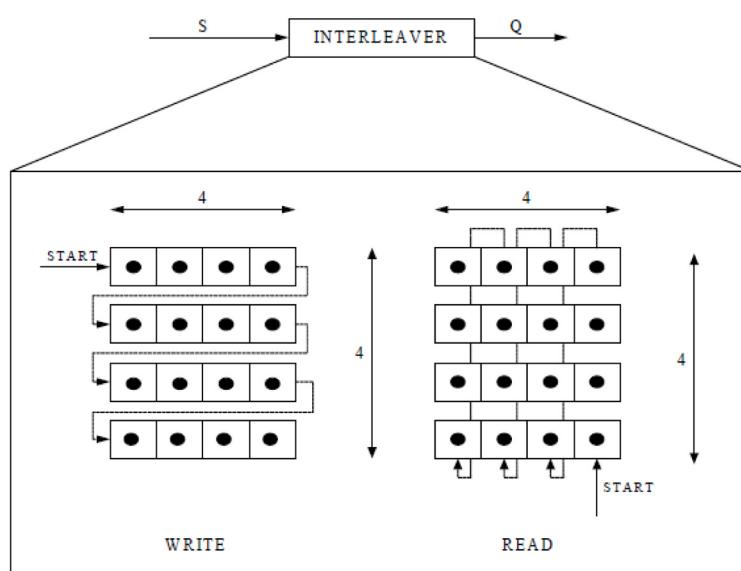


Figure 20-15—The interleaving block

The complete sequence of code-symbols $S = \{s(i)\}$, $0 \leq i \leq N-1$, is passed to the interleaver as N_{BLOCK} consecutive subsequences $A^{(p)}$, where $0 \leq p \leq N_{\text{BLOCK}}-1$, $N_{\text{BLOCK}} = N/16$, and N is a nonzero integer multiple of 16, as described in 20.3.5. The subsequence $A^{(0)}$ shall be passed to the interleaver first in time, and the subsequence $A^{(N_{\text{BLOCK}}-1)}$ shall be passed to the interleaver last in time.

Each subsequence $A^{(p)} = \{a^{(p)}(j)\}$ contains exactly 16 code-symbols and shall be derived according to the following equation:

$$a^{(p)}(j) = s(p \times 16 + j)$$

where $0 \leq j \leq 15$.

For each subsequence $A^{(p)}$ passed to the interleaver, the corresponding subsequence $Q^{(p)} = \{q^{(p)}(k)\}$ exiting the interleaver shall be computed as follows:

$$q^{(p)}(k) = a^{(p)}(t)$$

where

$$0 \leq k \leq 15$$

$$t = 15 - 4 \times (k \bmod 4) - \left\lfloor \frac{k}{4} \right\rfloor$$

The function $\lfloor x \rfloor = \text{floor}(x)$ returns the largest integer value not greater than x .

The complete sequence of interleaved code-symbols is derived as $Q = \{Q^{(0)}, Q^{(1)}, \dots, Q^{(N_{\text{BLOCK}}-1)}\}$.

20.4 Data whitening for SUN FSK

Support for data whitening is optional. Data whitening for the SUN FSK PHY shall use the procedure described in 17.2.3.

20.5 Mode switch mechanism for SUN FSK

The mode switch mechanism is optional.

The mode switch mechanism is enabled by setting the Mode Switch field to one. The SUN FSK mode switch PPDUs are transmitted on *phyCurrentChannelInfo*, as defined in 12.3.2, and the PPDUs containing the PSDUs are transmitted on the channel that corresponds to the same center frequency used for the SUN FSK mode switch PPDUs, as represented in the example in Table 20-14. If the center frequency of the mode used at the start of the frame is a valid center frequency for the new mode, then the same center frequency shall be used. The channel of the new PHY operating mode shall be the one with center frequency closest to that of the original channel used for the mode switch PPDUs. If there are two channels that are equally distant from the original channel, the higher channel shall be used. When a SUN FSK mode switch PPDUs, as described in Figure 20-2, is received, a device that supports mode switching shall change its mode of operation to the new mode defined in the SUN FSK mode switch PPDUs, in order to receive the following packet. If a device does not support mode switch or mode switch is not enabled (*phySunModeSwitchEnable* is FALSE), it shall drop the frame.

Table 20-14—An example of mapping between *phySunModeSwitchParameterEntries[]* and *ModeSwitchDescriptor*

<i>phySunModeSwitchParameterEntries[]</i>	Mode Switch Operation (Source mode -> Target mode)	ModeSwitchDescriptor		
		Settling Delay (μs)	SecondaryFsk PreambleLength	Secondary FskSfd
0	FSK->FSK	20	0	FALSE
1	FSK->4-FSK	40	0	FALSE
2	FSK->OFDM	160	n/a	n/a
3	FSK->O-QPSK	80	n/a	n/a

When changing from the current operating mode to the new mode, a settling delay may exist. The settling delay shall be in the range of 500 μs to 1.5 ms. The settling delay value is part of a ModeSwitchDescriptor, as described in Table 12-13. The value specified in the Mode Switch Parameter field of the PHR, as described in Figure 20-5, is the index of the PIB attribute array *phySunModeSwitchParameterEntries*, as

defined in 12.3.11, which contains the elements of the ModeSwitchDescriptor. How the Mode Switch Parameter field maps to ModeSwitchDescriptor is exemplified in Table 20-14. For the mode switch operation of FSK->FSK, the symbol rate is changed. For the mode switch operation of FSK->4-FSK, the modulation order and/or the symbol rate is changed. The Mode Switch Parameter table may be defined by the next higher layer.

Transmission of the new mode PPDU shall start SettlingDelay from the end of the mode switch PPDU. The SettlingDelay shall be the value indicated in the Mode Switch Parameter field in the mode switch PPDU. The reception and rejection of the following packet follows the same mechanism described in 6.6.2. After the new mode PPDU has been received, the receiver shall return to the previous operating mode within a LIFS period based on the symbol period of the new mode PPDU, depending on the received frame length, as described in 6.3.1. Also, if no PPDU is received in the new mode after the specified settling delay plus LIFS period, the receiver shall return to the previous operating mode within a SIFS or LIFS period. If the transmission of an Ack frame is requested by the transmitter, the Ack frame is transmitted using the current PHY mode.

The sequence of the SUN FSK mode switch PPDU, the optional settling delay, and the PPDU transmitted in the new PHY mode is shown in Figure 20-16. During the settling time of the new PHY mode, the device may perform a CCA before transmission to determine the new channel is clear.

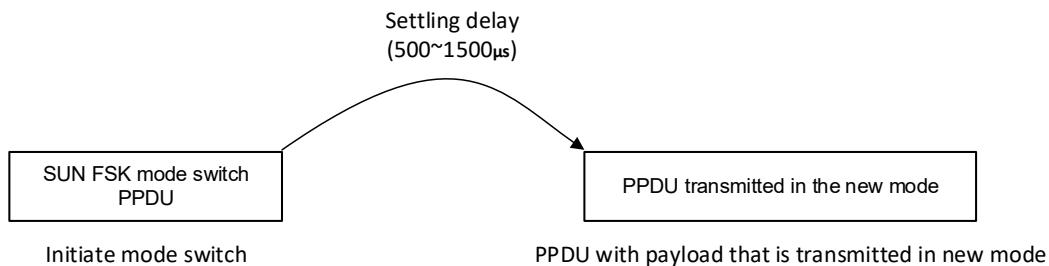


Figure 20-16—Transmitting sequence between SUN FSK mode switch PPDU and the new mode PPDU

Devices employing the mode switch mechanism shall meet the MAC timing requirements specified in Table 20-1, using the symbol period of the PHY mode prior to the mode switch.

The frequency band is not changed by the PHY mode switch mechanism.

For example, the channel frequency alignment for the 915 MHz band is shown in Table 20-15.

Table 20-15—Channel alignment for 915 MHz band

SUN FSK or SUN OFDM (200 kHz channel spacing)	SUN FSK or SUN OFDM (400 kHz channel spacing)	SUN OFDM (800 kHz channel spacing)	SUN O-QPSK
902.2	—	—	—
902.4	902.4	—	—
902.6	—	—	—
902.8	902.8	902.8	—
903.0	—	—	—
903.2	903.2	—	—

Table 20-15—Channel alignment for 915 MHz band (*continued*)

SUN FSK or SUN OFDM (200 kHz channel spacing)	SUN FSK or SUN OFDM (400 kHz channel spacing)	SUN OFDM (800 kHz channel spacing)	SUN O-QPSK
903.4	—	—	—
903.6	903.6	903.6	—
903.8	—	—	—
904.0	904.0	—	904.0
904.2	—	—	—
904.4	904.4	904.4	—
904.6	—	—	—
904.8	904.8	—	—
905.0	—	—	—
905.2	905.2	905.2	—
905.4	—	—	—
905.6	905.6	—	—
905.8	—	—	—
906.0	906.0	906.0	906.0
906.2	—	—	—
906.4	906.4	—	—
906.6	—	—	—
906.8	906.8	906.8	—
907.0	—	—	—
907.2	907.2	—	—
907.4	—	—	—
907.6	907.6	907.6	—
907.8	—	—	—
908.0	908.0	—	908.0
908.2	—	—	—
908.4	908.4	908.4	—
908.6	—	—	—
908.8	908.8	—	—
909.0	—	—	—
909.2	909.2	909.2	—
909.4	—	—	—
909.6	909.6	—	—
909.8	—	—	—

Table 20-15—Channel alignment for 915 MHz band (*continued*)

SUN FSK or SUN OFDM (200 kHz channel spacing)	SUN FSK or SUN OFDM (400 kHz channel spacing)	SUN OFDM (800 kHz channel spacing)	SUN O-QPSK
910.0	910.0	910.0	910.0
etc.	etc.	etc.	etc.

20.6 SUN FSK PHY RF requirements

20.6.1 Operating frequency range

The SUN FSK PHY operates in the bands given in Table 20-7 and Table 20-8.

20.6.2 Regulatory compliance

It is the responsibility of the implementer to verify that the device is in compliance with all regulatory requirements in the geographic region where the device is deployed or sold. Conformance with this standard does not guarantee compliance with the relevant regulatory requirements that may apply.

20.6.3 Radio frequency tolerance

The single-sided clock frequency tolerance T at the transmitter shall be as follows:

$$T \leq \min\left(\frac{T_0 \times R \times h \times F_0}{R_0 \times h_0 \times F}, 50 \times 10^{-6}\right)$$

for all combinations of R , h , and F and for each mode supported by the device, where

- R is the symbol rate, in ksymbol/s
- h is the modulation index
- F is the carrier frequency, in megahertz
- R_0 is 50 ksymbol/s
- h_0 is 1
- F_0 is 915 MHz
- T_0 is 30×10^{-6} for modes in all bands, except at 2450 MHz for which the value of T_0 is 40×10^{-6}

20.6.4 Channel switch time

Channel switch time shall be less than or equal to 500 μ s. The channel switch time is defined as the time elapsed when changing to a new channel, including any required settling time.

20.6.5 Transmitter symbol rate

The transmitter symbol rate tolerance shall be less than or equal to $\pm 300 \times 10^{-6}$. The peak transmitter symbol rate jitter shall be less than or equal to $\pm 40 \times 10^{-6}$. Transmitted packets shall have symbol rates within the specified symbol rate tolerance, and all symbols within the packet shall be within the symbol rate tolerance relative to the average symbol rate of all the symbols in the packet. The symbol rate jitter is

measured as the standard deviation of symbol edges from the nominal symbol edge position for the symbol rate used by the transmitter.

20.6.6 Transmit spectral mask

The transmit spectral content is the ratio of the total transmitted out-of-channel power to the total transmitted in-channel power in a given integration bandwidth.

When operating mode #1 with 100 kHz channel spacing or operating mode #3 with 200 kHz channel spacing or operating mode #5 with 400 kHz channel spacing are used as specified in Table 20-7 and Table 20-8, offset frequencies M_1 and M_2 and the integrated bandwidth (with respect to the M_1 and M_2 offset frequencies) are defined as follows:

The integration bandwidth shall be equal to $5/8 \times S$, where S is the channel spacing, expressed in units of hertz.

$$M_1 = 9/16 \times S \times (1 + h)$$

$$M_2 = 9/8 \times S \times (1 + h)$$

where h is the modulation index for 2-level modulation.

The transmit spectral content at M_1 and M_2 for the above specified operating modes shall be less than -20 dB and -35 dB, respectively.

Otherwise, for all other operating modes specified in Table 20-7, Table 20-8, Table 20-9, and Table 20-10, the offset frequencies M_1 and M_2 and the integrated bandwidth shall be defined as follows:

The integration bandwidth shall be equal to $1.5 \times R$, where R is the symbol rate, expressed in units of hertz.

Out-of-channel power shall be measured at two offset frequencies relative to the carrier frequency. The offset frequencies M_1 and M_2 are defined as follows:

$$M_1 = 1.5 \times R \times (1 + h)$$

$$M_2 = 3 \times R \times (1 + h)$$

where h is the modulation index for 2-level modulation and three times the modulation index for 4-level modulation.

The transmit spectral content at M_1 and M_2 shall be less than -25 dB and -35 dB, respectively.

The modulated signal shall use a PN data pattern of 511 bits or longer.

The spectrum analyzer settings for this measurement shall be as follows: the resolution bandwidth is 1 kHz, the video bandwidth is 1 kHz or greater, and the detector is RMS.

20.6.7 Receiver sensitivity

The SUN FSK receiver sensitivity shall be better than S , where S , for binary modulation, is defined as follows:

$$S = \left(S_0 + 10 \log \left[\frac{R}{R_0} \right] \right) \text{ dBm}$$

where

- S_0 is -91 without FEC and -97 with FEC
- R_0 is 50 kb/s
- R is the data rate, in kb/s

See 11.1.8 for additional information on receiver sensitivity.

20.6.8 Receiver interference rejection

The adjacent designated channels are those on either side of the desired designated channel that are closest in frequency to the desired designated channel. The alternate designated channel is more than one removed from the desired designated channel in the operational frequency band.

The adjacent channel rejection shall be measured as follows: the desired signal shall be a compliant SUN FSK PHY signal, as defined in 20.3, of pseudo-random data at the center frequency of the desired channel. The desired signal is input to the receiver at a level 3 dB above the receiver sensitivity given in 20.6.7.

In either the adjacent or the alternate channel, an unmodulated carrier in the center of that channel is input at the following level relative to the level of the desired signal:

- The adjacent channel rejection shall be greater than or equal to 10 dB.
- The alternate channel rejection shall be greater than or equal to 30 dB.

The test shall be performed for only one interfering signal at a time. The receiver shall meet the error rate criteria defined in 11.1.8 under these conditions.

20.6.9 TX-to-RX turnaround time

The SUN FSK PHY shall meet the requirements for TX-to-RX turnaround time as defined in 11.2.2.

20.6.10 RX-to-TX turnaround time

The SUN FSK PHY shall meet the requirements for RX-to-TX turnaround time as defined in 11.2.3.

20.6.11 Transmit power

A transmitter shall be capable of transmitting at a power level of at least -3 dBm. Devices should transmit lower power when possible in order to reduce interference to other devices and systems.

The maximum transmit power is limited by local regulatory bodies.

20.6.12 Receiver maximum input level of desired signal

The SUN FSK PHY shall have a receiver maximum input level greater than or equal to -20 dBm using the measurement defined in 11.2.5.

20.6.13 Receiver ED

The SUN FSK PHY shall provide the receiver ED measurement as described in 11.2.6.

20.6.14 LQI

The SUN FSK PHY shall provide the LQI measurement as described in 11.2.7.

21. SUN OFDM PHY

21.1 Introduction

The SUN OFDM PHY supports data rates ranging from 12.5 kb/s to 2400 kb/s. The subcarrier spacing is constant and is equal to 10416.6 Hz.

The symbol rate is 8.3 ksymbols/s , which corresponds to 120 μs per symbol. This symbol period is to be used for *a Turnaround Time*.

The symbol period used for MAC timing parameters (*macLifsPeriod* and *macSifsPeriod*) shall be the symbol period of SUN FSK operating mode #1 specified in Table 20-1.

This PHY includes four options, each one being characterized by the number of active tones during the PHR or PSDU. The total signal bandwidth for each option ranges from 1.2 MHz down to less than 200 kHz.

Two examples of encoding a packet for the SUN OFDM PHY are given in “Examples of IEEE Std 802.15.4 PHY encodings” [B10].

21.2 PPDU format for SUN OFDM

21.2.1 General

The SUN OFDM PPDU shall be formatted as illustrated in Figure 21-1.



Figure 21-1—Format of the SUN OFDM PPDU

The PHY Payload field shall be formatted as illustrated in Figure 21-2.



Figure 21-2—Format of the PHY Payload field

21.2.2 Short Training field (STF)

21.2.2.1 Frequency domain STF

Table 21-1 shows the frequency domain representation of the STF for Option 1. The scaling factor used in Table 21-1 is $\sqrt{\frac{104}{12}}$.

Table 21-1—Frequency domain representation of Option 1 STF_freq(0)

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-64	0	-32	-2.9439	0	0	32	2.9439
-63	0	-31	0	1	0	33	0
-62	0	-30	0	2	0	34	0

Table 21-1—Frequency domain representation of Option 1 STF_freq(0) (continued)

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-61	0	-29	0	3	0	35	0
-60	0	-28	0	4	0	36	0
-59	0	-27	0	5	0	37	0
-58	0	-26	0	6	0	38	0
-57	0	-25	0	7	0	39	0
-56	0	-24	2.9439	8	2.9439	40	-2.9439
-55	0	-23	0	9	0	41	0
-54	0	-22	0	10	0	42	0
-53	0	-21	0	11	0	43	0
-52	0	-20	0	12	0	44	0
-51	0	-19	0	13	0	45	0
-50	0	-18	0	14	0	46	0
-49	0	-17	0	15	0	47	0
-48	-2.9439	-16	2.9439	16	-2.9439	48	2.9439
-47	0	-15	0	17	0	49	0
-46	0	-14	0	18	0	50	0
-45	0	-13	0	19	0	51	0
-44	0	-12	0	20	0	52	0
-43	0	-11	0	21	0	53	0
-42	0	-10	0	22	0	54	0
-41	0	-9	0	23	0	55	0
-40	-2.9439	-8	2.9439	24	2.9439	56	0
-39	0	-7	0	25	0	57	0
-38	0	-6	0	26	0	58	0
-37	0	-5	0	27	0	59	0
-36	0	-4	0	28	0	60	0
-35	0	-3	0	29	0	61	0
-34	0	-2	0	30	0	62	0
-33	0	-1	0	31	0	63	0

Table 21-2 shows the frequency domain representation of the STF for Option 2. The scaling factor used in the table is $\sqrt{\frac{52}{12}}$.

Table 21-2—Frequency domain representation of Option 2 STF_freq(1)

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-32	0	-16	-2.0817	0	0	16	2.0817
-31	0	-15	0	1	0	17	0
-30	0	-14	0	2	0	18	0
-29	0	-13	0	3	0	19	0
-28	0	-12	2.0817	4	2.0817	20	-2.0817
-27	0	-11	0	5	0	21	0
-26	0	-10	0	6	0	22	0
-25	0	-9	0	7	0	23	0
-24	-2.0817	-8	2.0817	8	-2.0817	24	2.0817
-23	0	-7	0	9	0	25	0
-22	0	-6	0	10	0	26	0
-21	0	-5	0	11	0	27	0
-20	-2.0817	-4	2.0817	12	2.0817	28	0
-19	0	-3	0	13	0	29	0
-18	0	-2	0	14	0	30	0
-17	0	-1	0	15	0	31	0

Table 21-3 shows the frequency domain representation of the STF for Option 3. The scaling factor used in the table is $\sqrt{\frac{26}{6}}$.

Table 21-3—Frequency domain representation of Option 3 STF_freq(2)

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-16	0	-8	2.0817	0	0	8	2.0817
-15	0	-7	0	1	0	9	0
-14	0	-6	0	2	0	10	0
-13	0	-5	0	3	0	11	0
-12	2.0817	-4	2.0817	4	-2.0817	12	-2.0817
-11	0	-3	0	5	0	13	0
-10	0	-2	0	6	0	14	0
-9	0	-1	0	7	0	15	0

Table 21-4 shows the frequency domain representation of the STF for Option 4. The scaling factor used in the table is $\sqrt{\frac{14}{6}}$.

Table 21-4—Frequency domain representation of Option 4 STF_freq(3)

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-8	0	-4	1.5275	0	0	4	1.5275
-7	0	-3	0	1	0	5	0
-6	1.5275	-2	1.5275	2	-1.5275	6	-1.5275
-5	0	-1	0	3	0	7	0

21.2.2.2 Time domain STF generation

Given a sequence of N samples $f(n)$, indexed by $n = 0, \dots, N - 1$, the discrete Fourier transform (DFT) is defined as $F(k)$, where $k = 0, \dots, N - 1$:

$$F(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} f(n) e^{-j2\pi kn/N}$$

The sequence $f(n)$ can be calculated from $F(k)$ using the inverse discrete Fourier transform (IDFT), where the k values numbered from 0 to $(N / 2) - 1$ correspond to tones numbered from 0 to $(N / 2) - 1$ and the k values numbered from $(N / 2)$ to $(N - 1)$ correspond to tones numbered from $-(N / 2)$ to -1 , respectively:

$$f(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} F(k) e^{j2\pi nk/N}$$

The time domain STF for Option-n ($n = 1, 2, 3, 4$) is obtained as follows:

$$\text{STF_time(Option-n)} = \text{IDFT}(\text{STF_freq(Option-n)})$$

The CP is then prepended to the OFDM symbol.

21.2.2.3 Time domain STF repetition

There are four STF OFDM symbols, and the last half of the fourth OFDM symbol is negated in the time domain. For Options 2, 3, and 4, the CP is one-quarter of the OFDM symbol. Therefore, for Options 2 and 3, there are 18 repetitions of the quarter STF symbol followed by the last half of the fourth OFDM symbol, which is negated in the time domain. For Option 4, there are nine repetitions of the half STF symbol followed by the last half of the fourth OFDM symbol, which is negated in the time domain.

For Option 1, the CP is also one-quarter symbol, and the STF repetition is eight times per STF symbol. Therefore, there are 36 repetitions of one-eighth STF symbol in the four STF symbols followed by the last half of the fourth OFDM symbol, which is negated in the time domain.

Figure 21-3 shows the STF structure for all four options. Each s in Figure 21-3 represents one time-domain repetition of a subsequence of different length for SUN OFDM Option 1, Options 2 and 3, and Option 4.

	STF OFDM symbol	STF OFDM symbol	STF OFDM symbol	STF OFDM symbol
Option 1 1/8 Cycle	S -S -S -S -S			
Option 2 & 3 1/4 Cycle	S -S -S			
Option 4 1/2 Cycle	S -S			

Figure 21-3—Structure of STF for SUN OFDM for Options 1, 2, 3, and 4

21.2.2.4 STF normalization

The STF uses a lesser number of tones than the PHY Payload field. Hence, normalization of the frequency domain STF is required to balance the STF power with that of the rest of the packet. In order to have the same power as the PHY Payload field, the normalization value is as follows:

$$\sqrt{\frac{N_{\text{active}}}{N_{\text{stf}}}}$$

where

N_{active} is the number of used subcarriers in the rest of the OFDM packet for the particular DFT option
 N_{stf} is the number of subcarriers used in the STF

Power boosting shall be applied to the STF symbols in order to aid preamble detection. The boost should be a multiplication by 1.25, which is approximately 1.94 dB.

21.2.3 Long Training field (LTF)

21.2.3.1 Frequency domain LTF

Table 21-5 shows the frequency domain representation of the long training field (LTF) for Option 1.

Table 21-5—Frequency domain representation of Option 1 LTF_freq(0)

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-64	0	-32	-1	0	0	32	-1
-63	0	-31	-1	1	1	33	-1
-62	0	-30	-1	2	-1	34	-1
-61	0	-29	1	3	1	35	1
-60	0	-28	1	4	-1	36	1
-59	0	-27	-1	5	1	37	1
-58	0	-26	-1	6	1	38	1

Table 21-5—Frequency domain representation of Option 1 LTF_freq(0) (continued)

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-57	0	-25	-1	7	-1	39	1
-56	0	-24	-1	8	-1	40	1
-55	0	-23	-1	9	1	41	-1
-54	0	-22	1	10	-1	42	-1
-53	0	-21	1	11	1	43	-1
-52	-1	-20	-1	12	1	44	-1
-51	1	-19	1	13	1	45	-1
-50	1	-18	-1	14	1	46	-1
-49	-1	-17	-1	15	-1	47	1
-48	-1	-16	1	16	1	48	-1
-47	-1	-15	-1	17	1	49	1
-46	-1	-14	1	18	1	50	1
-45	1	-13	1	19	1	51	-1
-44	1	-12	1	20	1	52	1
-43	-1	-11	1	21	-1	53	0
-42	-1	-10	-1	22	1	54	0
-41	1	-9	-1	23	-1	55	0
-40	1	-8	1	24	1	56	0
-39	1	-7	1	25	-1	57	0
-38	-1	-6	-1	26	1	58	0
-37	-1	-5	1	27	-1	59	0
-36	1	-4	1	28	1	60	0
-35	1	-3	-1	29	1	61	0
-34	-1	-2	1	30	-1	62	0
-33	-1	-1	1	31	1	63	0

Table 21-6 shows the frequency domain representation of the LTF for Option 2.

Table 21-6—Frequency domain representation of Option 2 LTF_freq(1)

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-32	0	-16	1	0	0	16	1
-31	0	-15	-1	1	1	17	-1
-30	0	-14	1	2	-1	18	-1

Table 21-6—Frequency domain representation of Option 2 LTF_freq(1) (continued)

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-29	0	-13	1	3	1	19	-1
-28	0	-12	-1	4	1	20	-1
-27	0	-11	-1	5	-1	21	-1
-26	-1	-10	-1	6	1	22	1
-25	-1	-9	1	7	-1	23	-1
-24	-1	-8	1	8	-1	24	-1
-23	-1	-7	-1	9	1	25	-1
-22	1	-6	1	10	-1	26	1
-21	1	-5	1	11	1	27	0
-20	1	-4	1	12	1	28	0
-19	-1	-3	-1	13	-1	29	0
-18	1	-2	-1	14	-1	30	0
-17	-1	-1	-1	15	1	31	0

Table 21-7 shows the frequency domain representation of the LTF for Option 3.

Table 21-7—Frequency domain representation of Option 3 LTF_freq(2)

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-16	0	-8	1	0	0	8	-1
-15	0	-7	1	1	-1	9	1
-14	0	-6	1	2	-1	10	1
-13	1	-5	1	3	1	11	-1
-12	-1	-4	1	4	-1	12	-1
-11	1	-3	1	5	1	13	1
-10	-1	-2	1	6	1	14	0
-9	1	-1	-1	7	-1	15	0

Table 21-8 shows the frequency domain representation of the LTF for Option 4.

Table 21-8—Frequency domain representation of Option 4 LTF_freq(3)

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-8	0	-4	1	0	0	4	1
-7	1	-3	-1	1	-1	5	-1
-6	-1	-2	1	2	1	6	-1
-5	1	-1	1	3	1	7	-1

21.2.3.2 Time domain LTF generation

The time domain LTF for Option-n ($n = 1, 2, 3, 4$) is obtained as follows:

$$\text{LTF_time}(\text{Option-}n) = \text{IDFT}(\text{LTF_freq}(\text{Option-}n)).$$

A half symbol CP is prepended to two consecutive copies of the base symbol as shown in Figure 21-4. For more details, see 21.4.8.

The time-domain LTF structure is shown in Figure 21-4, and T_{DFT} is the duration of the base symbol.

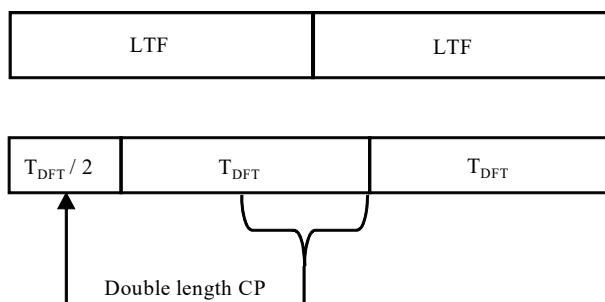


Figure 21-4—Structure of LTF for SUN OFDM

21.2.3.3 LTF normalization

Power boosting is not used by the LTF.

21.2.4 PHR

The PHR field shall be formatted as illustrated in Figure 21-5. All multibit fields are unsigned integers and shall be processed MSB first. The PHR is processed starting from the leftmost bit (i.e., starting with b0).

Bits: 0–4	5	6–16	17–18	19–20	21	22–29	30–35
Rate	Reserved	Frame Length	Reserved	Scrambler	Reserved	HCS	Tail

Figure 21-5—PHY header fields for SUN OFDM

The PHR occupies symbols for each of the OFDM options as described in Table 21-9, for *phyOfdmInterleaving* PIB attribute. For OFDM Option 1 and OFDM Option 2, the PHR shall be transmitted using MCS Level 0. For OFDM Option 3, MCS Level 0, the PHR shall be transmitted using MCS Level 0, and for MCS Level 1 or higher, the PHR shall be transmitted using MCS Level 1. For OFDM Option 4, MCS Level 0 and MCS Level 1, the PHR shall be transmitted using MCS Level 0, and for MCS Level 2 and higher, the PHR shall be transmitted using MCS Level 2. The PHR is sent to the convolutional encoder starting from the leftmost bit in Figure 21-5 to the rightmost bit.

Table 21-9—PHR Symbols for SUN OFDM PHY options

OFDM Option	MCS Level	<i>phyOfdmInterleaving</i>	PHR Symbols
1	0–6	0	3
2	0–6	0	6
3	1–6	0	6
	0	0	12
4	2–6	0	6
	0–1	0	24
1	0–6	1	4
2	0–6	1	8
3	1–6	1	6
	0	1	12
4	2–6	1	6
	0–1	1	24

The Rate field is set to the numerical value of the MCS Level, as described in 21.4, expressed in binary format, transmitted MSB first. The data rates for each OFDM bandwidth option can be found in 21.3.

The Frame Length field is an unsigned integer that shall be set to the total number of octets contained in the PSDU (prior to FEC encoding). The Frame Length field shall be transmitted MSB first.

The Scrambler field specifies the scrambling seed, as described in 21.4.11.

The header check sequence (HCS) field is an 8-bit CRC taken over the PHR fields.

The HCS shall be computed using the first 22 bits of the PHR. The HCS shall be calculated using the polynomial $G_8(x) = x^8 + x^2 + x + 1$.

The HCS is the one's complement of the modulo-2 sum of the two remainders in a) and b):

- a) The remainder resulting from $[x^k(x^7+x^6+\dots+1)]$ divided (modulo 2) by $G_8(x)$, where the value k is the number of bits in the calculation field.
- b) The remainder resulting from the calculation field contents, treated as a polynomial, multiplied by x^8 and then divided (modulo 2) by $G_8(x)$.

At the transmitter, the initial remainder of the division shall be preset to all ones and is then modified via division of the calculation field by the generator polynomial $G_8(x)$. The one's complement of this remainder is the HCS field. The HCS field is transmitted commencing with the coefficient of the highest order term. An example of HCS generation is given in “Examples of IEEE Std 802.15.4 PHY encodings” [B10].

The Tail field consists of all zeros, which is intended for Viterbi decoder flushing, as described in 21.4.9.

21.2.5 PSDU field

The PSDU field contains the encoded PSDU.

21.3 Data rates for SUN OFDM

There are four OFDM options, each with a different number of active tones. All devices supporting a particular option (1, 2, 3, or 4) shall support all BPSK and QPSK MCS levels for that option. All 16 quadrature amplitude modulation (QAM) MCS levels are optional.

The various data rates are shown in Table 21-10. The nominal bandwidth is calculated by multiplying {the number of active tones + 1 for the DC tone} by {the subcarrier spacing}.

Table 21-10—Data rates for SUN OFDM PHY

Parameter	OFDM Option 1	OFDM Option 2	OFDM Option 3	OFDM Option 4
Nominal bandwidth (kHz)	1094	552	281	156
Channel spacing (kHz)	1200	800	400	200
DFT size	128	64	32	16
Active tones	104	52	26	14
# Pilot tones	8	4	2	2
# Data tones	96	48	24	12
MCS0 (kb/s) (BPSK rate 1/2 with 4x frequency repetition)	100	50	25	12.5
MCS1 (kb/s) (BPSK rate 1/2 with 2x frequency repetition)	200	100	50	25
MCS2 (kb/s) (QPSK rate 1/2 and 2x frequency repetition)	400	200	100	50
MCS3 (kb/s) (QPSK rate 1/2)	800	400	200	100
MCS4 (kb/s) (QPSK rate 3/4)	1200	600	300	150
MCS5 (kb/s) (16-QAM rate 1/2)	1600	800	400	200
MCS6 (kb/s) (16-QAM rate 3/4)	2400	1200	600	300

21.4 Modulation and coding for SUN OFDM

21.4.1 Reference modulator diagram

The reference modulator diagram is shown in Figure 21-6.

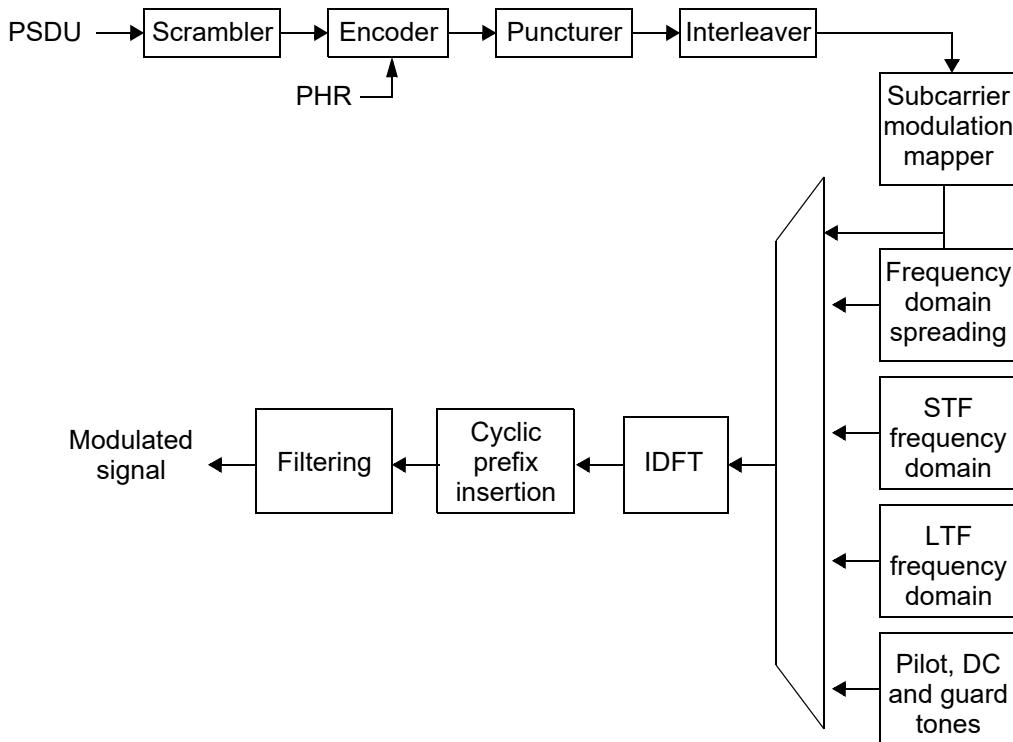


Figure 21-6—Reference modulator diagram for SUN OFDM

21.4.2 Bit-to-symbol mapping

Figure 21-7 shows the bit-to-symbol mapping for BPSK, QPSK, and 16-QAM.

The output values, d , are formed by multiplying the resulting $(I + jQ)$ value by a normalization factor K_{MOD} :

$$d = (I + jQ) \times K_{\text{MOD}}$$

The normalization factor, K_{MOD} , depends on the base modulation mode, as described in Table 21-11. The purpose of the normalization factor is to achieve the same average power for all mappings.

Table 21-11—Modulation-dependent normalization factor K_{MOD}

Modulation	K_{MOD}
BPSK	1
QPSK	$1/(\sqrt{2})$
16-QAM	$1/(\sqrt{10})$

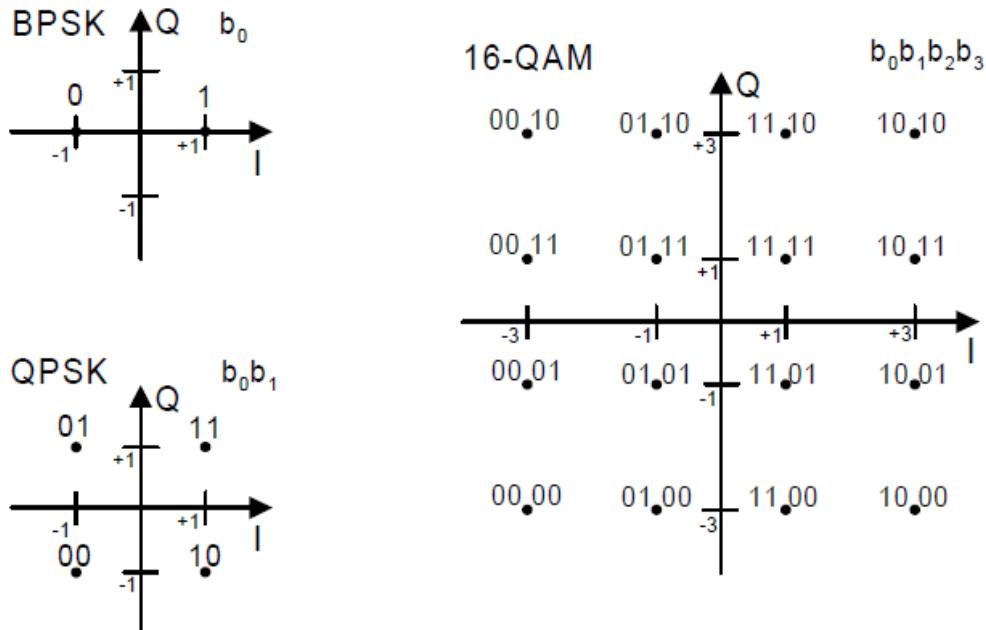


Figure 21-7—Bit-to-symbol mapping for SUN OFDM

21.4.3 PIB attribute values for *phySymbolsPerOctet*²⁴

The number of symbols per octet depends on both the MCS level and the OFDM option, as represented in Table 21-12.

Table 21-12—*phySymbolsPerOctet* values for SUN OFDM PHY

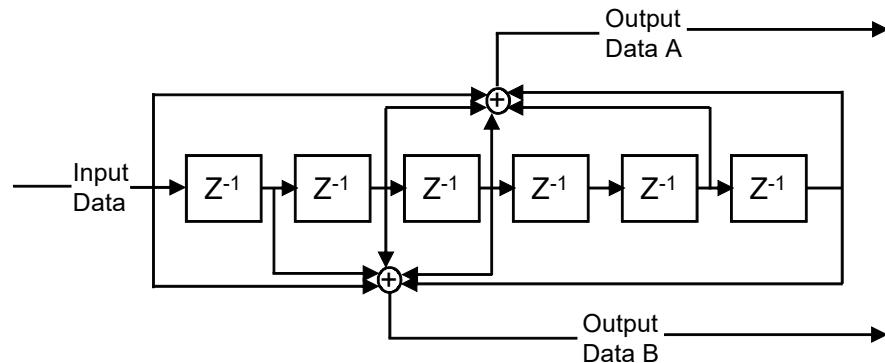
MCS		OFDM Option			
MCS Level	Description	1	2	3	4
0	BPSK 1/2 rate coded and 4x frequency repetition	2/3	4/3	8/3	16/3
1	BPSK 1/2 rate coded and 2x frequency repetition	1/3	2/3	4/3	8/3
2	QPSK 1/2 rate coded and 2x frequency repetition	1/6	1/3	2/3	4/3
3	QPSK 1/2 rate coded	1/12	1/6	1/3	2/3
4	QPSK 3/4 rate coded	1/18	1/9	2/9	4/9
5	16-QAM 1/2 rate coded	1/24	1/12	1/6	1/3
6	16-QAM 3/4 rate coded	1/36	1/18	1/9	2/9

21.4.4 FEC

The PHY Payload field shall be coded with a convolutional encoder of coding rate $R = 1/2$ or $3/4$, corresponding to the desired data rate. The convolutional encoder shall use the generator polynomials

²⁴ PHY PIB attributes are defined in 12.3.

expressed in octal representation, $g_0 = 133_8$ and $g_1 = 171_8$, of rate $R = 1/2$, as shown in Figure 21-8. The convolutional encoder shall be initialized to the all zeros state before encoding the PHR and then reset to the all zeros state before encoding the PSDU.



Convolutional Encoder: Rate $\frac{1}{2}$, constraint length K=7
Octal generator polynomials [133 , 171]

Figure 21-8—Rate 1/2 convolutional encoder

The device shall support also coding rates of $R = 3/4$, derived by puncturing, as shown in Figure 21-9.

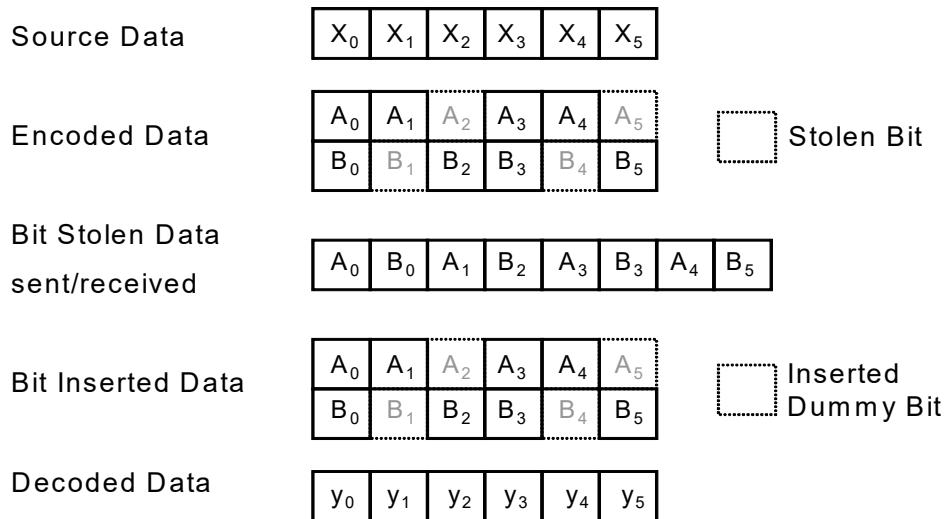


Figure 21-9—Puncturing for rate 3/4

21.4.5 Interleaver

The interleaving process consists of two permutations. The index of the coded bit before the first permutation shall be denoted as k ; i shall be the index after the first and before the second permutation; and j shall be the index after the second permutation, just prior to modulation mapping. The coded bits are written at the index given by j , and read out sequentially. The index i is defined as follows:

$$i = \left(\frac{N_{\text{cbps}}}{N_{\text{row}}} \right) \times [k \bmod(N_{\text{row}})] + \text{floor} \left(\frac{k}{N_{\text{row}}} \right)$$

where

- N_{cbps} is the number of coded bits per symbol before any frequency spreading
- k is $0, 1, 2, \dots, (N_{\text{cbps}} - 1)$
- N_{row} is 12 when no frequency spreading is used or $12 / (\text{spreading factor})$ when spreading is used

The index j is defined as follows:

$$j = s \times \text{floor}\left(\frac{i}{s}\right) + \left[i + N_{\text{cbps}} - \text{floor}\left(\frac{N_{\text{row}} \times i}{N_{\text{cbps}}}\right)\right] \bmod(s)$$

where

- N_{cbps} is the number of coded bits per symbol before any frequency spreading
- i is $0, 1, 2, \dots, N_{\text{cbps}} - 1$
- N_{row} is 12 when no frequency spreading is used or $12 / (\text{spreading factor})$ when spreading is used

and

$$s = \max\left(\frac{N_{\text{bpsc}}}{2}, 1\right)$$

where N_{bpsc} is the number of bits per subcarrier and has the values 1, 2, and 4 for BPSK, QPSK, and 16-QAM, respectively.

Devices shall support an interleaving depth of one symbol, which is associated with a value of zero for the PIB attribute *phyOfdmInterleaving*, as defined in 12.3.12. The values for N_{cbps} with *phyOfdmInterleaving* set to zero are shown in Table 21-13. In this case, N_{cbps} is defined as follows: 24, 48, 96, 192, or 384 bits for Option 1; 12, 24, 48, 96, or 192 bits for Option 2; 6, 12, 24, 48, or 96 bits for Option 3; 3, 6, 12, 24, or 48 bits for Option 4.

Table 21-13— N_{cbps} for SUN OFDM with *phyOfdmInterleaving* = 0

MCS level	OFDM Option 1	OFDM Option 2	OFDM Option 3	OFDM Option 4
0	24	12	6	3
1	48	24	12	6
2	96	48	24	12
3	192	96	48	24
4	192	96	48	24
5	384	192	96	48
6	384	192	96	48

Devices may support an interleaving depth of the number of symbols equal to the frequency domain spreading factor, which is associated with a value of one for the PIB attribute *phyOfdmInterleaving*. The frequency domain spreading factor can be one, two, or four. In this case, N_{cbps} is defined as follows: 96 bits

for BPSK, 192 bits for QPSK, or 384 bits for 16-QAM in Option 1; 48 bits for BPSK, 96 bits for QPSK, or 192 bits for 16-QAM in Option 2; 24 bits for BPSK, 48 bits for QPSK, or 96 bits for 16-QAM in Option 3; 12 bits for BPSK, 24 bits for QPSK, or 48 bits for 16-QAM in Option 4.

21.4.6 Frequency spreading

21.4.6.1 Overview

Frequency spreading is a method of replicating PSK symbols on different carriers.

The DFT index 0 is the center of the channel, as defined in 11.1.3.9. The positive DFT indices are mapped to the higher frequencies:

$$\text{center} + N \times \text{tone spacing}$$

where N is the DFT index.

The negative DFT indices are mapped to the lower frequencies:

$$\text{center} - N \times \text{tone spacing}$$

21.4.6.2 Frequency spreading by 2x

The device shall offer the possibility to create a 2x repetition through frequency spreading.

The spreading is performed by first separating out the data tones from the pilot tones. The data tones are renumbered from $-N_d/2$ to -1 and 1 to $N_d/2$, where N_d is the number of data tones in an OFDM symbol. As an example with Option 3, there are two pilot tones and 24 data tones with indices from -13 to 13 excluding the DC tone. Therefore, the data tones are renumbered as $d_{-12}, d_{-11}, d_{-10}, d_{-9}, d_{-8}, d_{-7}, d_{-6}, d_{-5}, d_{-4}, d_{-3}, d_{-2}, d_{-1}$, and $d_1, d_2, d_3, d_4, d_5, d_6, d_7, d_8, d_9, d_{10}, d_{11}, d_{12}$. The DC tone is omitted since it is not used in any of the OFDM options.

The data tones to be transmitted in the OFDM symbol are placed into the positive data tones (numbered from 1 to $N_d/2$). Phase rotations are applied after copying the data tones to the negative frequencies, in order to reduce the peak-to-average power ratio of the OFDM symbol with frequency spreading. The data tones are as follows:

$$d_{(k-[N_d/2]-1)} = d_k e^{[j2\pi(2 \times k - 1)/4]}$$

where k is $1, \dots, N_d/2$.

21.4.6.3 Frequency spreading by 4x

The device shall offer the possibility to create a 4x repetition through frequency spreading.

As with frequency spreading by 2x, the data tones are separated from the pilot tones and renumbered. The data tones to be transmitted in the OFDM symbol are placed into the lower half of the positive data tones (numbered from 1 to $N_d/4$). Phase rotations are applied after copying the data tones to the negative frequencies and upper half of the positive frequencies, in order to reduce the peak-to-average power ratio of the OFDM symbol with frequency spreading.

$$d_{(k+N_d/4)} = d_k e^{[j2\pi(k-1)/4]}$$

where k is $1, \dots, N_d/4$.

$$d_{(k-[N_d/2]-1)} = d_k e^{[j2\pi(2 \times k - 1)/4]}$$

where k is $1, \dots, N_d/4$.

$$d_{(k-[N_d/4]-1)} = d_k e^{[j2\pi(3 \times k - 1)/4]}$$

where k is $1, \dots, N_d/4$.

21.4.6.4 No spreading

The device shall offer the possibility to map a symbol into tones without frequency spreading.

The data tones to be transmitted in the OFDM symbol are placed into the negative data tones (numbered from $-N_d/2$ to -1) followed by the positive data tones (numbered 1 to $N_d/2$).

21.4.7 Pilot tones/null tones

The number of pilot and null tones for each OFDM option are defined as shown in Table 21-14.

Table 21-14—Number of pilot and null tones for SUN OFDM PHY

	OFDM Option 1	OFDM Option 2	OFDM Option 3	OFDM Option 4
Active tones	104	52	26	14
# Pilot tones	8	4	2	2
# Data tones	96	48	24	12
#DC null tones	1	1	1	1

The pilot tones shall be transmitted with different shifts in the frequency domain, in order to enable channel estimation when the channel is changing due to Doppler. Immediately after the second LTF, the pilot shifts change every OFDM symbol to the next set. For Options 1, 2, 3, and 4, there are 13, 7, 7, and 4 pilot sets, respectively. Figure 21-10 illustrates how the pilot sets cycle through the sets for Option 1. Figure 21-11 illustrates how the pilot sets cycle through the sets for Options 2 and 3. Figure 21-12 illustrates how the pilot sets cycle through the sets for Option 4. The pilot sets for each option are unique to that option. The long vertical lines show visually when each cycle through the pilots sets is complete.

The DC tone is numbered as 0.

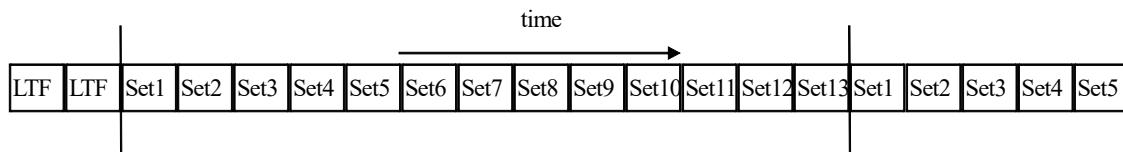


Figure 21-10—Pilot tone sets for Option 1

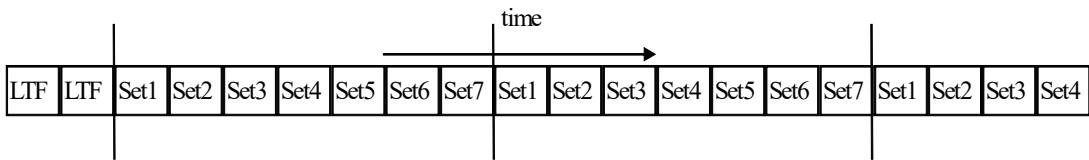


Figure 21-11—Pilot tone sets for Options 2 and 3

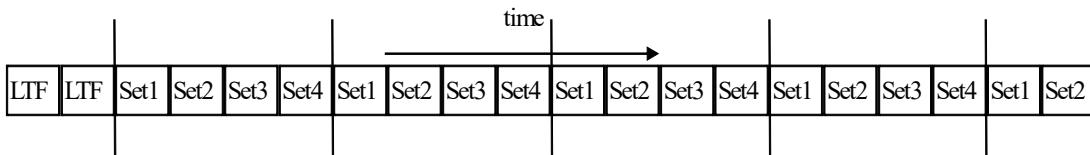


Figure 21-12—Pilot tone sets for Option 4

For Option 1, the device shall use the 13 sets of pilot tones consisting of the subcarriers shown in Table 21-15. The subcarriers for pilot and data are numbered as –52 to 52 with the DC tone unused.

Table 21-15—Pilot tones for Option 1

Pilot set 1	-38	-26	-14	-2	10	22	34	46
Pilot set 2	-46	-34	-22	-10	2	14	26	38
Pilot set 3	-42	-30	-18	-6	6	18	30	42
Pilot set 4	-50	-38	-26	-14	-2	10	22	50
Pilot set 5	-46	-34	-22	-10	2	14	34	46
Pilot set 6	-42	-30	-18	-6	6	18	26	38
Pilot set 7	-50	-38	-26	-14	-2	30	42	50
Pilot set 8	-46	-34	-22	-10	10	22	34	46
Pilot set 9	-42	-30	-18	-6	2	14	26	38
Pilot set 10	-50	-38	-26	6	18	30	42	50
Pilot set 11	-46	-34	-14	-2	10	22	34	46
Pilot set 12	-42	-30	-22	-10	2	14	26	38
Pilot set 13	-50	-18	-6	6	18	30	42	50

For Option 2, the device shall use the seven sets of pilot tones consisting of the subcarriers shown in Table 21-16. The subcarriers for pilot and data are numbered as –26 to 26 with the DC tone unused.

Table 21-16—Pilot tones for Option 2

Pilot set 1	–14	–2	10	22
Pilot set 2	–22	–10	2	14
Pilot set 3	–18	–6	6	18
Pilot set 4	–26	–14	–2	26
Pilot set 5	–22	–10	10	22
Pilot set 6	–18	–6	2	14
Pilot set 7	–26	6	18	26

For Option 3, the device shall use the seven sets of pilot tones consisting of the subcarriers shown in Table 21-17. The subcarriers for pilot and data are numbered as –13 to 13 with the DC tone unused.

Table 21-17—Pilot tones for Option 3

Pilot set 1	–7	7
Pilot set 2	–11	3
Pilot set 3	–3	11
Pilot set 4	–9	5
Pilot set 5	–5	9
Pilot set 6	–13	1
Pilot set 7	–1	13

For Option 4, the device shall use the four sets of pilot tones consisting of the subcarriers shown in Table 21-18. The subcarriers for pilot and data are numbered as –7 to 7 with the DC tone unused.

Table 21-18—Pilot tones for Option 4

Pilot set 1	–3	5
Pilot set 2	–7	1
Pilot set 3	–5	3
Pilot set 4	–1	7

The data carried on the pilot tones shall be determined by a pseudo-noise sequence PN9 with the seed “111111111”, as described in 20.4. The first output bit is assigned to the most negative index in Set 1. For example, for Option 3, the first output bit from the PN9 sequence is assigned to the pilot symbol with index –7, and the second output bit is assigned to the pilot symbol with index 7. Table 21-19 shows the

mapping from PN9 bits to the pilot BPSK symbols for all OFDM options and MCS levels. Index n starts after the LTF from zero and is increased by one every pilot subcarrier.

Table 21-19—Mapping from PN9 sequence to pilot BPSK symbols

Input bit (PN9_n)	BPSK symbol
0	$-1 + (0 \times j)$
1	$1 + (0 \times j)$

21.4.8 Cyclic prefix (CP)

For the STF, the CP is defined in 21.2.2.3. For the LTF, the CP is defined in 21.2.3.2. For the remaining OFDM symbols, a CP shall be prepended to each base symbol. The duration of the CP (24 μs) shall be one-quarter of the base symbol (96 μs). The CP is a replication of the last 24 μs of the base symbol. The CP is illustrated in Figure 21-13. In Figure 21-13, N is the number of samples in the base symbol, while L is the length of the CP that is added to the base symbol.

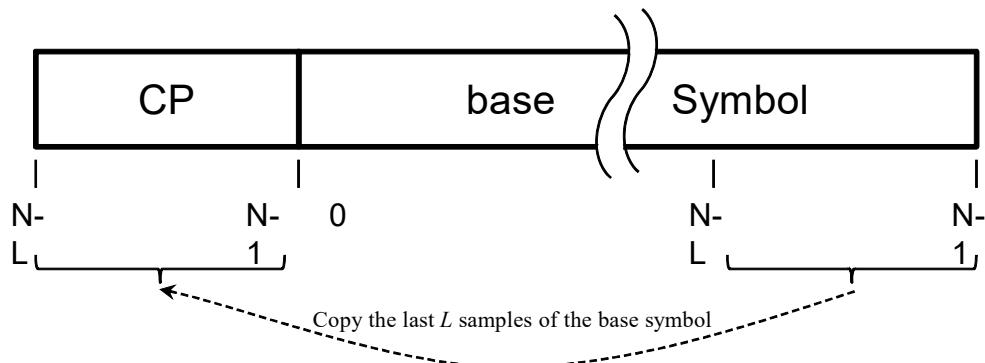


Figure 21-13—Cyclic prefix (CP)

21.4.9 PPDU Tail field

The PPDU Tail field shall be six bits of 0, which are required to return the convolutional encoder to the *zero state*. This procedure reduces the error probability of the convolutional decoder, which relies on future bits when decoding and which may be not be available past the end of the message. The PPDU Tail field shall be produced by replacing six scrambled zero bits following the message end with six non-scrambled zero bits.

21.4.10 Pad field

The number of bits in the PHY Payload field shall be a multiple of N_{cbps} . To achieve that, the length of the message is extended so that it becomes a multiple of N_{dbps} , the number of data bits per OFDM symbol; this case is associated with a value of zero for the PIB attribute *phyOfdmInterleaving*, as defined in 12.3.12. At least six bits are appended to the message in order to accommodate the PPDU Tail field, as described in 21.4.9. The number of OFDM symbols, N_{SYM} ; the number of bits in the PHY Payload field, $N_{\text{PHYPayload}}$; and the number of bits in the Pad field, N_{Pad} , are computed from the length, of the PSDU in octets (length is equal to the content of the Frame Length field in Figure 21-5) as follows:

For Option 4 and MCS Level 0:

$$N_{\text{SYM}} = 2 \times \text{ceiling}[(8 \times \text{Length} + 6)/(2 \times N_{\text{dbps}})]$$

For all other modes:

$$N_{\text{SYM}} = \text{ceiling}[(8 \times \text{Length} + 6)/N_{\text{dbps}}]$$

For all the modes:

$$N_{\text{Data}} = N_{\text{SYM}} \times N_{\text{dbps}}$$

$$N_{\text{Pad}} = N_{\text{Data}} - (8 \times \text{Length} + 6)$$

The function ceiling() returns the smallest integer value greater than or equal to its argument value. The appended bits, the Pad field, are set to zeros and are subsequently scrambled with the rest of the bits in the PHY Payload field.

If a device supports an interleaving depth of the number of symbols equal to the frequency domain spreading factor (SF), which is associated with a value of one for the PIB attribute *phyOfdmInterleaving*, the length of the message is extended so that it becomes a multiple of N_{dbps} , the number of data bits per SF OFDM symbols, defined as $N_{\text{dbps}} = N_{\text{cbps}} \times$ coding rate (R), where N_{cbps} is the number of coded bits per SF OFDM symbols as in 21.4.5. The number of sets of SF OFDM symbols, N_{SYMSF} , and $N_{\text{PHYPayload}}$ are computed as follows:

$$N_{\text{SYMSF}} = SF \times \text{ceiling}[(8 \times \text{Length} + 6)/N_{\text{dbps}}]$$

where SF may be 1, 2, or 4.

$$N_{\text{PHYPayload}} = N_{\text{SYMSF}} \times N_{\text{dbps}}/SF$$

N_{Pad} is computed as before. In the case of the PHR, 36 should be set instead of $8 \times \text{Length} + 6$ as in 21.2.4.

21.4.11 Scrambler and scrambler seeds

The input to the scrambler is the data bits followed by the PPDU Tail field and then Pad field. The scrambler uses a PN9 sequence that is shown in Figure 17-2. The PN9 scrambler is initialized by one of four seeds. The seed to be used for the scrambler is indicated by two bits in the PHR, as shown in Table 21-20. The leftmost value of the scrambling seed in Table 21-20 is placed into the leftmost delay element in Figure 17-2.

Table 21-20—Initial seeds to be used for PN9 scrambler

MSB scrambler (bit 19 of PHR) ^a	LSB scrambler (bit 20 of PHR) ^a	Scrambling seed
0	0	0 0 0 0 1 0 1 1 1
1	0	0 0 0 0 1 1 1 0 0
0	1	1 0 1 1 1 0 1 1 1
1	1	1 0 1 1 1 1 1 0 0

^a See 21.2.4.

The scrambled bits are found using an XOR operation of each of the input bits with the PN9 sequence:

$$\text{bit}_n = (\text{input bit}_n) \text{ XOR } (\text{PN9}_n)$$

After scrambling, the PPDU Tail field is set to all zeros.

21.5 SUN OFDM PHY RF requirements

21.5.1 Operating frequency range

The SUN OFDM PHY operates in the following bands:

- 470–510 MHz
- 779–787 MHz
- 863–870 MHz
- 865–868 MHz
- 866–869 MHz
- 870–876 MHz
- 902–928 MHz
- 902–928(alternate) MHz
- 902–907.5 MHz and 915–928 MHz
- 915–928 MHz
- 915–921 MHz
- 915–918 MHz
- 917–923.5 MHz
- 919–923 MHz
- 920–928 MHz
- 920.5–924.5 MHz
- 920–925 MHz
- 2400–2483.5 MHz

21.5.2 Transmit power spectral density (PSD) mask

The SUN OFDM transmit PSD mask shall conform with local regulations.

21.5.3 Receiver sensitivity

The sensitivity requirements, as described in 11.1.8, for every option and MCS level are shown in Table 21-21.

Table 21-21—Sensitivity requirements for OFDM options and MCS levels

MCS Level	Description	Option 1	Option 2	Option 3	Option 4
0	BPSK $\frac{1}{2}$ rate coded and 4x frequency repetition	-103 dBm	-105 dBm	-108 dBm	-111 dBm
1	BPSK $\frac{1}{2}$ rate coded and 2x frequency repetition	-100 dBm	-103 dBm	-105 dBm	-108 dBm
2	QPSK $\frac{1}{2}$ rate coded and 2x frequency repetition	-97 dBm	-100 dBm	-103 dBm	-105 dBm
3	QPSK $\frac{1}{2}$ rate coded	-94 dBm	-97 dBm	-100 dBm	-103 dBm
4	QPSK $\frac{3}{4}$ rate coded	-91 dBm	-94 dBm	-97 dBm	-100 dBm
5	16-QAM $\frac{1}{2}$ rate coded	-88 dBm	-91 dBm	-94 dBm	-97 dBm
6	16-QAM $\frac{3}{4}$ rate coded	-85 dBm	-88 dBm	-91 dBm	-94 dBm

21.5.4 Adjacent channel rejection

The definition of an adjacent channel can be found in 13.3.5.

The adjacent channel rejection shall be measured as follows. The desired signal shall be a compliant SUN OFDM PHY signal of pseudo-random data, and the adjacent channel interferer shall be a compliant SUN OFDM PHY signal of pseudo-random data using the same MCS as the desired signal at a power level stronger than the desired signal, as indicated in Table 21-22 for each MCS. The desired signal is input to the receiver at a level 3 dB above the maximum allowed receiver sensitivity given in 21.5.3, and the PER shall be as defined in 11.1.8.

Table 21-22—SUN OFDM adjacent and alternate channel rejection

MCS level	Adjacent channel rejection (dB)	Alternate channel rejection (dB)
0	10	26
1	10	26
2	7	23
3	7	23
4	5	21
5	2	18
6	-2	14

21.5.5 Alternate channel rejection

The adjacent channels are those on either side of the desired channel that are closest in frequency to the desired channel. The alternate channel is more than one removed from the desired channel in the operational frequency band.

The alternate channel rejection shall be measured as follows. The desired signal shall be a compliant SUN OFDM PHY signal of pseudo-random data, and the alternate channel interferer shall be a compliant SUN OFDM PHY signal of pseudo-random data using the same MCS as the desired signal at a power level stronger than the desired signal, as indicated in Table 21-22, for each MCS. The desired signal is input to the receiver at a level 3 dB above the maximum allowed receiver sensitivity given in 21.5.3, and the PER shall be as defined in 11.1.8.

21.5.6 TX-to-RX turnaround time

The SUN OFDM PHY shall meet the requirements for TX-to-RX turnaround time as defined in 11.2.2.

21.5.7 RX-to-TX turnaround time

The SUN OFDM PHY shall meet the requirements for RX-to-TX turnaround time as defined in 11.2.3.

21.5.8 EVM definition

The relative constellation RMS error averaged over subcarriers, symbols, and packets shall not exceed the values shown in Table 21-23.

Table 21-23—EVM requirements for SUN OFDM PHY

MCS	RMS error
MCS0	-10 dB
MCS1	-10 dB
MCS2	-10 dB
MCS3	-10 dB
MCS4	-13 dB
MCS5	-16 dB
MCS6	-19 dB

The transmit modulation accuracy test shall be performed by instrumentation capable of converting the transmitted signal into a stream of complex samples. The sampled signal shall be processed in a manner similar to an actual receiver, according to the following steps, or an equivalent procedure:

- a) Detect the start of packet.
- b) Detect the transition from STF to LTF, and establish fine timing (with one sample resolution).
- c) Estimate the coarse and fine frequency offsets.
- d) De-rotate the packet according to estimated frequency offset.
- e) Estimate the complex channel response coefficients for each of the subcarriers.

- f) For each data OFDM symbol, transform the symbol into subcarrier received values and divide each subcarrier value with the estimated channel response coefficient.
- g) For each N_d data-carrying subcarrier, find the closest constellation point, and compute the squared Euclidean distance from it.
- h) Compute the RMS average of all errors in a packet:

$$\text{RMS}_{\text{error}} = 20 \log_{10} \left(\frac{1}{N_f} \sum_{i=1}^{N_f} \sqrt{\frac{\sum_{j=1}^{N_{\text{SYM}}} \sum_{k \in U_D} \Delta(i, j, k)^2}{N_d \times N_{\text{SYM}} \times P_0}} \right)$$

with

$$\Delta(i, j, k)^2 = [I(i, j, k) - I_0(i, j, k)]^2 + [Q(i, j, k) - Q_0(i, j, k)]^2$$

where

N_{SYM} is the number of OFDM symbols in the packet

N_f is the number of packets used for the measurement

$U_D = \{-N_d/2, \dots, -1, 1, \dots, N_d/2\}$ is the index set of data tones

$[I_0((i, j, k), Q_0(i, j, k))]$ denotes the ideal symbol point of the i th packet, j th OFDM symbol of the packet, and k th subcarrier of the OFDM symbol in the complex plane

$[I((i, j, k), Q(i, j, k))]$ denotes the observed point of the i th packet, j th OFDM symbol of the packet, and k th tone of the OFDM symbol in the complex plane

P_0 is the average power of the constellation

The test shall be performed over at least $N_f = 20$ packets. The payload of the packets under test shall contain $N_{\text{SYM}} = 16$ OFDM symbols. Random data shall be used for the payload.

21.5.9 Transmit center frequency and symbol tolerance

The transmit center frequency tolerance shall be $\pm 20 \times 10^{-6}$ maximum. The symbol clock frequency tolerance shall also be $\pm 20 \times 10^{-6}$ maximum. The transmit center frequency and the symbol clock frequency shall be derived from the same reference oscillator.

21.5.10 Transmit power

A transmitter shall be capable of transmitting at least -3 dBm. Devices should transmit lower power when possible in order to reduce interference to other devices and systems.

The maximum transmit power is limited by local regulatory bodies.

21.5.11 Receiver maximum input level of desired signal

The SUN OFDM PHY shall have a receiver maximum input level greater than or equal to -20 dBm using the measurement defined in 11.2.5.

21.5.12 Receiver ED

The SUN OFDM PHY shall provide the receiver ED measurement as described in 11.2.6.

21.5.13 LQI

The SUN OFDM PHY shall provide the LQI measurement as described in 11.2.7.

21.5.14 Cca

The recommended value of *phyCcaDuration* is 16000 divided by the nominal bandwidth in kilohertz, as specified in Table 21-10.

22. SUN O-QPSK PHY

22.1 Introduction

The SUN O-QPSK PHY supports multiple PSDU data rates within each supported frequency band, as described in Table 11-1.

For all frequency bands, spreading is obtained by DSSS applying various spreading factors. For the 780 MHz, 915 MHz, 915 MHz-a, 915 MHz-b, 915 MHz-c, 917 MHz, and 2450 MHz frequency bands, the SUN O-QPSK PHY may support an alternative spreading mode for the PSDU, called MDSSS.

For the 780 MHz, 915 MHz, and 2450 MHz frequency bands, the SUN O-QPSK PHY supports communication with legacy devices according to the specifications in Clause 13, as described in 22.4.

A SUN O-QPSK compliant device shall support at least one of the frequency bands designated in Table 11-1.

For the SUN QPSK PHY, the symbol rate is defined as the bit rate of the SHR.

An example of encoding a packet for the SUN O-QPSK PHY is given in “Examples of IEEE Std 802.15.4 PHY encodings” [B10].

22.2 PPDU format for SUN O-QPSK

22.2.1 General

The SUN O-QPSK PPDU shall be formatted as illustrated in Figure 22-1.



Figure 22-1—Format of the SUN O-QPSK PHY PPDU

22.2.2 SHR field format

22.2.2.1 General

The SHR field shall be formatted as illustrated in Figure 22-2.

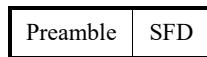


Figure 22-2—Format of the SHR

22.2.2.2 Preamble field format

The Preamble field shall contain a sequence of 56 bits, all zero, for the 780 MHz, 915 MHz, 915 MHz-a, 915 MHz-b, 915 MHz-c, 917 MHz, and 2450 MHz frequency bands. It shall contain a sequence of 32 bits, all zero, for the 470 MHz, 866 MHz, 867 MHz, 868 MHz, 870 MHz, 915 MHz-d, 915 MHz-e, 919 MHz, 920 MHz, 920 MHz-a, and 920 MHz-b frequency bands.

22.2.2.3 SFD field format

The SFD shall be the sequence described in Figure 22-3.

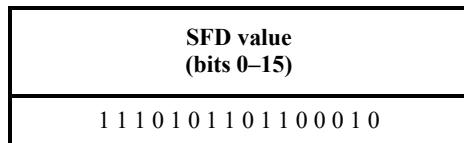


Figure 22-3—Format of the SFD field for the SUN O-QPSK PHY

22.2.3 PHR field format

The format of the PHR is shown in Figure 22-4.

Bits: 0	1–2	3–4	5–15	16–23
Spreading Mode	Rate Mode	Reserved	Frame Length	HCS

Figure 22-4—Format of the PHR for SUN O-QPSK

For the 780 MHz, 915 MHz, 915 MHz-a, 915 MHz-b, 915 MHz-c, 917 MHz, and 2450 MHz frequency bands, the Spreading Mode field shall be set to one if MDSSS is used for PSDU spreading, as described in 22.3.5. Otherwise, the Spreading Mode field shall be set to zero if DSSS is used for PSDU spreading, as described in 22.3.4. For the 470 MHz, 866 MHz, 867 MHz, 868 MHz, 870 MHz, 915 MHz-d, 915 MHz-e, 919 MHz, 920 MHz, 920 MHz-a, and 920 MHz-b frequency bands, the Spreading Mode field shall be set to zero, i.e., MDSSS is not supported.

The SUN O-QPSK PHY supports up to four different PSDU rate modes within each frequency band, and the rate mode is given by the Rate Mode field. Table 22-1 shows the mapping of the bit values to the rate mode.

Table 22-1—Rate mode mapping of the SUN O-QPSK PHY

Rate Mode field (b1, b2)	Rate mode
(0, 0)	0
(0, 1)	1
(1, 0)	2
(1, 1)	3

The Frame Length field specifies the total number of octets contained in the PSDU prior to FEC encoding.

The HCS field is calculated over the first 16 PHR bits, (b0, b1, ..., b15), where b0 is the PHR bit at bit string index 0 and b15 is the PHR bit at bit string index 15, as described in Figure 22-4. The HCS field is defined as follows:

$$HCS = (r_0, r_1, \dots, r_6, r_7)$$

for certain coefficients $r_0, r_1, \dots, r_6, r_7$. The computation of those coefficients is shown by the following algorithm.

The HCS shall be calculated using the following standard generator polynomial of degree 8:

$$G_8(x) = x^8 + x^2 + x + 1$$

The HCS shall be calculated as follows:

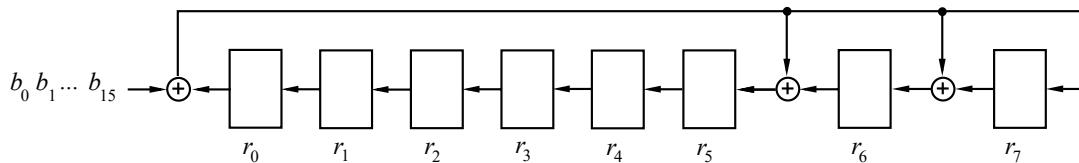
- Let $M(x) = b_0x^{15} + b_1x^{14} + \dots + b_{14}x + b_{15}$ be the polynomial representing the sequence of bits for which the checksum is to be computed.
- Multiply $M(x)$ by x^8 , giving the polynomial $x^8 \times M(x)$.
- Divide modulo 2 by the generator polynomial, $G_8(x)$, to obtain the remainder polynomial, $R(x) = r_0x^7 + r_1x^6 + \dots + r_6x + r_7$.

The HCS field is given by the coefficients of the remainder polynomial. An example HCS is shown in Figure 22-5.

Bits: 0	1	2	3	4	5–15	16–23
0	0	1	0	0	0 0 0 0 0 1 0 1 0 1 0	0 1 1 1 1 0 0 0

Figure 22-5—Example HCS for SUN O-QPSK

A typical implementation is depicted in Figure 22-6.



- 1) Initialize the remainder register (r_0, r_1, \dots, r_7) to zero.
- 2) Shift the sequence b_0, b_1, \dots, b_{15} into the divider beginning with b_0 .
- 3) After the last bit, b_{15} , is shifted into the divider, the remainder register contains the HCS: $(r_0, r_1, \dots, r_7) = (b_{16}, b_{17}, \dots, b_{23})$

Figure 22-6—Typical HCS implementation for SUN O-QPSK

22.2.4 PHY Payload field

The PHY Payload field contains the encoded PSDU.

22.3 Modulation and coding for SUN O-QPSK

22.3.1 Reference modulator

Figure 22-7 shows the reference modulator diagram for the SUN O-QPSK PHY.

The inputs to the reference modulator are the bit sequences of the SHR field, the PHR field, and the PSDU field. Processing of the SHR and PHR gives corresponding chip sequences c_{SHR} , as described in 22.3.2, and c_{PHR} , as described in 22.3.3, respectively. The bits of the PSDU field are processed by a dedicated signal flow depending on spreading mode, as described in 22.3.4 and 22.3.5. In either case, the corresponding chip

sequences will be extended by pilots, as described in 22.3.12, resulting in a final PSDU chip sequence c_{PSDU} . The concatenated sequence of chips belonging to the PPDU:

$$c_{\text{PPDU}} = \{c_{\text{SHR}}, c_{\text{PHR}}, c_{\text{PSDU}}\}$$

shall be O-QPSK modulated, as described in 22.3.13.

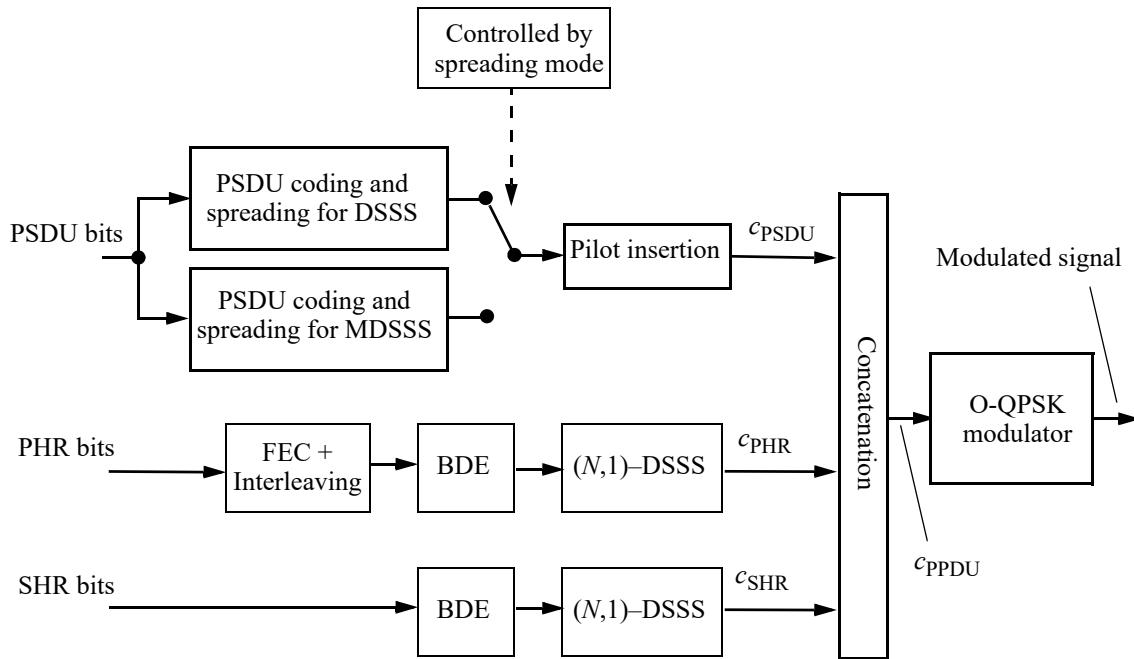


Figure 22-7—Reference modulator diagram

22.3.2 SHR coding and spreading

For the SHR bits, bit differential encoding (BDE), as described in 22.3.8, and subsequently $(N,1)$ -DSSS shall be applied, as described in 22.3.9.

Table 22-2 shows the spreading parameters of $(N,1)$ -DSSS bit-to-chip mapping.

Table 22-2—SHR coding and spreading parameters

Band designation (MHz)	Chip rate (kchip/s)	BDE	Spreading mode
470	100	yes	$(32,1)_0$ -DSSS
780	100	yes	$(32,1)_0$ -DSSS
	1000	yes	$(64,1)$ -DSSS
866	100	yes	$(32,1)_0$ -DSSS
867	100	yes	$(32,1)_0$ -DSSS
868	100	yes	$(32,1)_0$ -DSSS
870	100	yes	$(32,1)_0$ -DSSS

Table 22-2—SHR coding and spreading parameters (*continued*)

Band designation (MHz)	Chip rate (kchip/s)	BDE	Spreading mode
915	100	yes	(32,1) ₀ -DSSS
	1000	yes	(64,1)-DSSS
915-a	100	yes	(32,1) ₀ -DSSS
	1000	yes	(64,1)-DSSS
915-b	100	yes	(32,1) ₀ -DSSS
	1000	yes	(64,1)-DSSS
915-c	100	yes	(32,1) ₀ -DSSS
	1000	yes	(64,1)-DSSS
915-d	100	yes	(32,1) ₀ -DSSS
915-e	100	yes	(32,1) ₀ -DSSS
917	100	yes	(32,1) ₀ -DSSS
	1000	yes	(64,1)-DSSS
919	100	yes	(32,1) ₀ -DSSS
920	100	yes	(32,1) ₀ -DSSS
920-a	100	yes	(32,1) ₀ -DSSS
920-b	100	yes	(32,1) ₀ -DSSS
2450	2000	yes	(128,1)-DSSS

22.3.3 PHR coding and spreading

The PHR field, as described in Figure 22-4, shall be processed using FEC, as described in 22.3.6, and interleaving, as described in 22.3.7, resulting in 60 interleaved code bits. For the interleaved PHR code bits, BDE, as described in 22.3.8, and subsequently (N,1)-DSSS shall be applied, as described in 22.3.9.

Table 22-3 shows the spreading parameters of (N,1)-DSSS bit-to-chip mapping.

Table 22-3—PHR coding and spreading parameters

Band designation (MHz)	Chip rate (kchip/s)	BDE	Rate ½ FEC + interleaver	Spreading mode
470	100	yes	yes	(8,1) _{0/1} -DSSS
779	100	yes	yes	(8,1) _{0/1} -DSSS
	1000	yes	yes	(16,1) _{0/1} -DSSS
866	100	yes	yes	(8,1) _{0/1} -DSSS
867	100	yes	yes	(8,1) _{0/1} -DSSS

Table 22-3—PHR coding and spreading parameters (*continued*)

Band designation (MHz)	Chip rate (kchip/s)	BDE	Rate ½ FEC + interleaver	Spreading mode
868	100	yes	yes	(8,1) _{0/1} -DSSS
870	100	yes	yes	(8,1) _{0/1} -DSSS
915	100	yes	yes	(8,1) _{0/1} -DSSS
	1000	yes	yes	(16,1) _{0/1} -DSSS
915-a	100	yes	yes	(8,1) _{0/1} -DSSS
	1000	yes	yes	(16,1) _{0/1} -DSSS
915-b	100	yes	yes	(8,1) _{0/1} -DSSS
	1000	yes	yes	(16,1) _{0/1} -DSSS
915-c	100	yes	yes	(8,1) _{0/1} -DSSS
	1000	yes	yes	(16,1) _{0/1} -DSSS
915-d	100	yes	yes	(8,1) _{0/1} -DSSS
915-e	100	yes	yes	(8,1) _{0/1} -DSSS
917	100	yes	yes	(8,1) _{0/1} -DSSS
	1000	yes	yes	(16,1) _{0/1} -DSSS
919	100	yes	yes	(8,1) _{0/1} -DSSS
920	100	yes	yes	(8,1) _{0/1} -DSSS
920-a	100	yes	yes	(8,1) _{0/1} -DSSS
920-b	100	yes	yes	(8,1) _{0/1} -DSSS
2450	2000	yes	yes	(32,1) _{0/1} -DSSS

22.3.4 PSDU coding and spreading for DSSS

Figure 22-8 shows the signal flow when DSSS is applied to the PSDU (spreading mode set to DSSS).

The supported PSDU parameters for spreading mode DSSS are shown in Table 22-4. A SUN O-QPSK compliant device shall implement at least rate mode zero with spreading mode set to DSSS, as described in 22.3.4. All other possible combinations of rate mode and spreading mode, as described in 22.3.4 and 22.3.5, are optional.

The PSDU information bit shall be first processed using FEC as described in 22.3.6, delivering a sequence of code bits. The code bits shall be interleaved as described in 22.3.7. Depending on the frequency band and rate mode, spreading by DSSS with different spreading factors shall be applied.

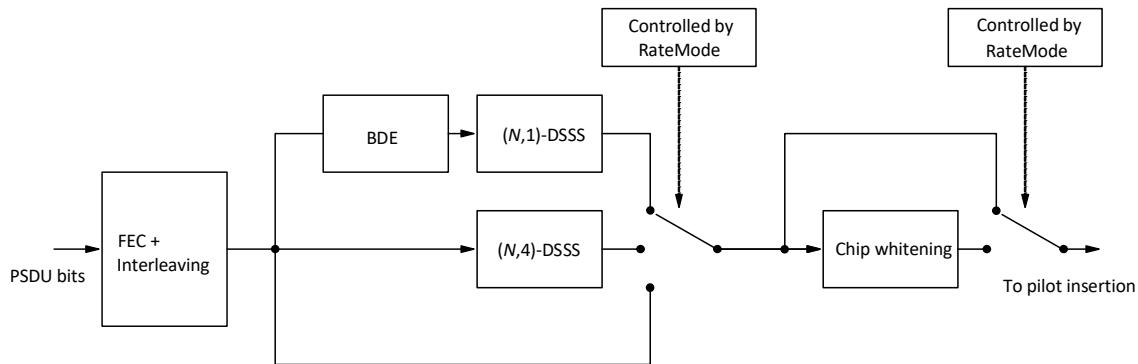


Figure 22-8—PSDU processing for DSSS

Table 22-4—PSDU parameters for spreading mode DSSS

Band designation (MHz)	Chip rate (kchip/s)	Rate mode	BDE	Spreading mode	Rate ½ FEC + interleaver	Data rate (kb/s)
470	100	0	yes	(8,1) _{0/1} -DSSS	yes	6.25
		1	yes	(4,1)-DSSS	yes	12.5
		2	yes	(2,1)-DSSS	yes	25
		3	no	none	yes	50
779	100	0	yes	(8,1) _{0/1} -DSSS	yes	6.25
		1	yes	(4,1)-DSSS	yes	12.5
		2	yes	(2,1)-DSSS	yes	25
		3	no	none	yes	50
	1000	0	yes	(16,1) _{0/1} -DSSS	yes	31.25
		1	no	(16,4)-DSSS	yes	125
		2	no	(8,4)-DSSS	yes	250
		3	no	none	yes	500
866	100	0	yes	(8,1) _{0/1} -DSSS	yes	6.25
		1	yes	(4,1)-DSSS	yes	12.5
		2	yes	(2,1)-DSSS	yes	25
		3	no	none	yes	50
867	100	0	yes	(8,1) _{0/1} -DSSS	yes	6.25
		1	yes	(4,1)-DSSS	yes	12.5
		2	yes	(2,1)-DSSS	yes	25
		3	no	none	yes	50

Table 22-4—PSDU parameters for spreading mode DSSS (continued)

Band designation (MHz)	Chip rate (kchip/s)	Rate mode	BDE	Spreading mode	Rate ½ FEC + interleaver	Data rate (kb/s)
868	100	0	yes	(8,1) _{0/1} -DSSS	yes	6.25
		1	yes	(4,1)-DSSS	yes	12.5
		2	yes	(2,1)-DSSS	yes	25
		3	no	none	yes	50
870	100	0	yes	(8,1) _{0/1} -DSSS	yes	6.25
		1	yes	(4,1)-DSSS	yes	12.5
		2	yes	(2,1)-DSSS	yes	25
		3	no	none	yes	50
915	100	0	yes	(8,1) _{0/1} -DSSS	yes	6.25
		1	yes	(4,1)-DSSS	yes	12.5
		2	yes	(2,1)-DSSS	yes	25
		3	no	none	yes	50
	1000	0	yes	(16,1) _{0/1} -DSSS	yes	31.25
		1	no	(16,4)-DSSS	yes	125
		2	no	(8,4)-DSSS	yes	250
		3	no	none	yes	500
915-a	100	0	yes	(8,1) _{0/1} -DSSS	yes	6.25
		1	yes	(4,1)-DSSS	yes	12.5
		2	yes	(2,1)-DSSS	yes	25
		3	no	none	yes	50
	1000	0	yes	(16,1) _{0/1} -DSSS	yes	31.25
		1	no	(16,4)-DSSS	yes	125
		2	no	(8,4)-DSSS	yes	250
		3	no	none	yes	500
915-b	100	0	yes	(8,1) _{0/1} -DSSS	yes	6.25
		1	yes	(4,1)-DSSS	yes	12.5
		2	yes	(2,1)-DSSS	yes	25
		3	no	none	yes	50
	1000	0	yes	(16,1) _{0/1} -DSSS	yes	31.25
		1	no	(16,4)-DSSS	yes	125
		2	no	(8,4)-DSSS	yes	250
		3	no	none	yes	500

Table 22-4—PSDU parameters for spreading mode DSSS (continued)

Band designation (MHz)	Chip rate (kchip/s)	Rate mode	BDE	Spreading mode	Rate ½ FEC + interleaver	Data rate (kb/s)
915-c	100	0	yes	(8,1) _{0/1} -DSSS	yes	6.25
		1	yes	(4,1)-DSSS	yes	12.5
		2	yes	(2,1)-DSSS	yes	25
		3	no	none	yes	50
	1000	0	yes	(16,1) _{0/1} -DSSS	yes	31.25
		1	no	(16,4)-DSSS	yes	125
		2	no	(8,4)-DSSS	yes	250
		3	no	none	yes	500
915-d	100	0	yes	(8,1)0/1-DSSS	yes	6.25
		1	yes	(4,1)-DSSS	yes	12.5
		2	yes	(2,1)-DSSS	yes	25
		3	no	none	yes	50
915-e	100	0	yes	(8,1)0/1-DSSS	yes	6.25
		1	yes	(4,1)-DSSS	yes	12.5
		2	yes	(2,1)-DSSS	yes	25
		3	no	none	yes	50
917	100	0	yes	(8,1) _{0/1} -DSSS	yes	6.25
		1	yes	(4,1)-DSSS	yes	12.5
		2	yes	(2,1)-DSSS	yes	25
		3	no	none	yes	50
	1000	0	yes	(16,1) _{0/1} -DSSS	yes	31.25
		1	no	(16,4)-DSSS	yes	125
		2	no	(8,4)-DSSS	yes	250
		3	no	none	yes	500
919	100	0	yes	(8,1)0/1-DSSS	yes	6.25
		1	yes	(4,1)-DSSS	yes	12.5
		2	yes	(2,1)-DSSS	yes	25
		3	no	none	yes	50
920	100	0	yes	(8,1) _{0/1} -DSSS	yes	6.25
		1	yes	(4,1)-DSSS	yes	12.5
		2	yes	(2,1)-DSSS	yes	25
		3	no	none	yes	50

Table 22-4—PSDU parameters for spreading mode DSSS (continued)

Band designation (MHz)	Chip rate (kchip/s)	Rate mode	BDE	Spreading mode	Rate ½ FEC + interleaver	Data rate (kb/s)
920-a	100	0	yes	(8,1)0/1-DSSS	yes	6.25
		1	yes	(4,1)-DSSS	yes	12.5
		2	yes	(2,1)-DSSS	yes	25
		3	no	none	yes	50
920-b	100	0	yes	(8,1)0/1-DSSS	yes	6.25
		1	yes	(4,1)-DSSS	yes	12.5
		2	yes	(2,1)-DSSS	yes	25
		3	no	none	yes	50
2450	2000	0	yes	(32,1) _{0/1} -DSSS	yes	31.25
		1	no	(32,4)-DSSS	yes	125
		2	no	(16,4)-DSSS	yes	250
		3	no	(8,4)-DSSS	yes	500

The first DSSS method applies BDE, as described in 22.3.8, to the interleaved code bits and subsequently the $(N,1)$ -bit-to-chip mapping as described in 22.3.9. The second DSSS method applies $(N,4)$ -bit-to-chip mapping to the interleaved code bits as described in 22.3.9. In this case, BDE shall not be applied, as described in Table 22-4. The highest PSDU data rate is obtained by bypassing BDE and spreading, as described in Figure 22-8 and Table 22-4.

When applying $(N,4)$ -DSSS, the sequence of interleaved PSDU code bits shall be extended by appending a minimum number of pad bits, such that the length of the extended interleaved PSDU code-bit sequence is a multiple of four. The pad bits shall be set to zero.

Depending on the frequency band and rate mode, the output sequence of the bit-to-chip mapper shall be whitened, as described in 22.3.11.

The relationship between the rate mode and the DataRate parameter of the MCPS-DATA.request primitive is described in Table 8-30.

22.3.5 PSDU coding and spreading for MDSSS

Figure 22-9 shows the signal flow when MDSSS is applied to the PSDU (spreading mode set to MDSSS). The supported PSDU parameters for spreading mode MDSSS are shown in Table 22-5. The combinations of rate mode and spreading mode described in this subclause are optional.

The use of FEC depends on the rate mode chosen, as described in Table 22-5. When FEC is used, the PSDU information bits shall be first processed using FEC, as described in 22.3.6, delivering a sequence of code bits. When FEC is enabled, the code bits shall be interleaved, as described in 22.3.7; otherwise, interleaving is bypassed. The rate mode also determines which $(N,8)$ -MDSSS spreading factor shall be used, as described in Table 22-5 and 22.3.10.

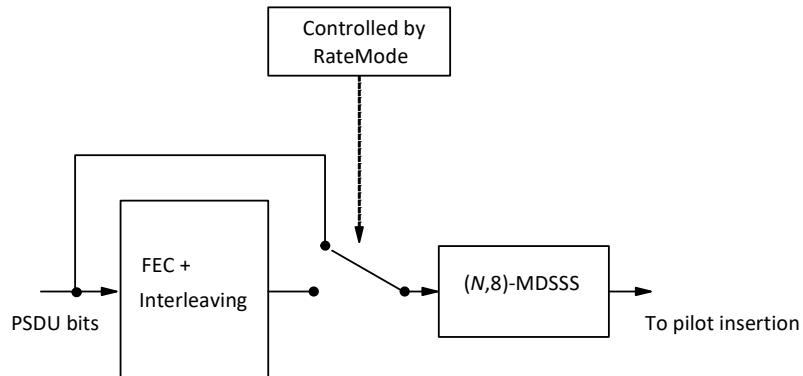


Figure 22-9—PSDU processing for MDSSS

Table 22-5—PSDU parameters for spreading mode MDSSS

Frequency band (MHz)	Chip rate (kchip/s)	Rate mode	BDE	Spreading mode	Rate $\frac{1}{2}$ FEC + interleaver	Data rate (kb/s)
470–510	not supported					
779–787	1000	0	no	(64,8)-MDSSS	yes	62.5
		1	no	(32,8)-MDSSS	yes	125
		2	no	(32,8)-MDSSS	no	250
		3	no	(16,8)-MDSSS	no	500
865–868	not supported					
866–869	not supported					
868–870	not supported					
870–876	not supported					
902–928	1000	0	no	(64,8)-MDSSS	yes	62.5
		1	no	(32,8)-MDSSS	yes	125
		2	no	(32,8)-MDSSS	no	250
		3	no	(16,8)-MDSSS	no	500
902–928 (alternate)	1000	0	no	(64,8)-MDSSS	yes	62.5
		1	no	(32,8)-MDSSS	yes	125
		2	no	(32,8)-MDSSS	no	250
		3	no	(16,8)-MDSSS	no	500
902–907.5 and 915–928	1000	0	no	(64,8)-MDSSS	yes	62.5
		1	no	(32,8)-MDSSS	yes	125
		2	no	(32,8)-MDSSS	no	250
		3	no	(16,8)-MDSSS	no	500

Table 22-5—PSDU parameters for spreading mode MDSSS (*continued*)

Frequency band (MHz)	Chip rate (kchip/s)	Rate mode	BDE	Spreading mode	Rate ½ FEC + interleaver	Data rate (kb/s)
915–928	1000	0	no	(64,8)-MDSSS	yes	62.5
		1	no	(32,8)-MDSSS	yes	125
		2	no	(32,8)-MDSSS	no	250
		3	no	(16,8)-MDSSS	no	500
915–921				not supported		
915–918				not supported		
917–923.5	1000	0	no	(64,8)-MDSSS	yes	62.5
		1	no	(32,8)-MDSSS	yes	125
		2	no	(32,8)-MDSSS	no	250
		3	no	(16,8)-MDSSS	no	500
919–923				not supported		
920–928				not supported		
920.5–924.5				not supported		
920–925				not supported		
2400–2483.5	2000	0	no	(128,8)-MDSSS	yes	62.5
		1	no	(64,8)-MDSSS	yes	125
		2	no	(64,8)-MDSSS	no	250
		3	no	(32,8)-MDSSS	no	500

When applying (N,8)-MDSSS, the sequence of interleaved PSDU code bits shall be extended by appending a minimum number of pad bits, such that the length of the extended interleaved PSDU code-bit sequence is a multiple of 8. The pad bits shall be set to zero.

The relationship between the spreading mode variable and the DataRate parameter of the MCPS-DATA.request primitive is described in Table 8-30.

22.3.6 FEC

FEC shall be applied to the bits of the PHR field.

For spreading mode set to DSSS, FEC shall be applied to the PSDU bits, as described in Table 22-4. For spreading mode set to MDSSS, FEC is enabled depending on rate mode, as described in Table 22-5.

When used, FEC shall employ rate 1/2 convolutional coding with constraint length $K=7$ using the following generator polynomials:

$$G_0(x) = 1 + x^2 + x^3 + x^5 + x^6$$

$$G_1(x) = 1 + x + x^2 + x^3 + x^6$$

The encoder is shown in Figure 22-10, where \oplus denotes modulo-2 addition.

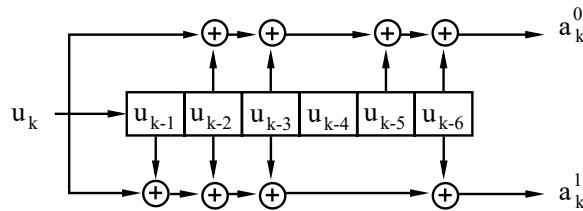


Figure 22-10—Convolutional encoder

Prior to convolutional encoding of the PHR information bits, as described in 22.2.3, the initial encoder state at $k=0$ shall be set to:

$$(u_{-1}, u_{-2}, \dots, u_{-6}) = (0, 0, 0, 0, 0, 0)$$

and the PHR information bit sequence shall be extended by a termination sequence of six zero bits as shown in Figure 22-11.

PHR bits	000000	PSDU bits	000000	pad bits
----------	--------	-----------	--------	----------

Figure 22-11—PHR and PSDU extension prior to encoding

Prior to the convolutional encoding of the PSDU, the sequence of PSDU information bits shall be extended by appending a termination sequence of six bits, all zero, and a sequence of additional pad bits as shown in Figure 22-11. The pad bits shall be set to zero and the number of pad bits, N_{PAD} , is computed from the number of blocks, N_B , the total number of uncoded bits, N_D , and the interleaver depth, N_{INTRLV} , as follows:

$$N_B = \text{ceiling}((8 \times \text{LENGTH} + 6)/(N_{\text{INTRLV}}/2))$$

$$N_D = N_B \times (N_{\text{INTRLV}}/2)$$

$$N_{\text{PAD}} = N_D - (8 \times \text{LENGTH} + 6)$$

The function ceiling() is a function that returns the smallest integer value greater than or equal to its argument value.

The sequence of extended information bits according to Figure 22-11 shall be passed to the convolutional encoder. The corresponding output sequence of code bits, z , shall be generated as follows:

$$z = \{ \dots a_k^0, a_k^1, a_{k+1}^0, a_{k+1}^1, a_{k+2}^0, a_{k+2}^1 \dots \} = \{ z_0, z_1, \dots, z_{2N_D + 59} \}$$

i.e., a_k^0 is preceding sample a_k^1 . The first sample, z_0 , shall be passed to the interleaver first in time, and the last sample, $z_{2N_D + 59}$, shall be passed to the interleaver last in time.

The number of code bits referring to a single interleaving block, N_{INTRLV} , is defined in 22.3.7.

22.3.7 Code-bit interleaving

Interleaving of PHR code bits shall be employed and is separated from the interleaving of the PSDU code bits. Since the PHR information bits are terminated, PHR code bits and PSDU code bits are independent code blocks.

Interleaving of PSDU code bits shall be employed in conjunction with PSDU FEC, in order to improve robustness against burst errors and to break correlation of consecutive bits when applying (N,4) or (N,8) bit-to-chip mapping. No PSDU code-bit interleaving shall be employed if PSDU FEC is not used, as described in Table 22-5.

The sequence of PHR code bits consists of a single sequence:

$$z^0 = \{z_0^0, \dots, z_{N_{\text{INTRLV}} - 1}^0\}$$

of length $N_{\text{INTRLV}} = 60$.

The sequence of PSDU code bits consists of N_B subsequences:

$$z^j = \{z_0^j, \dots, z_{N_{\text{INTRLV}} - 1}^j\} = \{z_{(j-1)N_{\text{INTRLV}} + 60}, \dots, z_{jN_{\text{INTRLV}} + 59}\} \text{ for } j = 1, \dots, N_B$$

where

N_B is the number of blocks, as defined in 22.3.6

N_{INTRLV} is shown in Table 22-6

In either case, the interleaver is defined by a permutation. The index of the code bits before the permutation shall be denoted by k , where $k = 0$ refers to the first sample, z_0^j , and $k = N_{\text{INTRLV}} - 1$ refers to the last sample, $z_{N_{\text{INTRLV}} - 1}^j$, passed to the interleaver for a given subsequence z^j . The index i shall be the index after the permutation. The permutation is defined by the following rule:

$$i = \frac{N_{\text{INTRLV}}}{\lambda} \times ((N_{\text{INTRLV}} - 1 - k) \bmod \lambda) + \text{floor} \left(\frac{N_{\text{INTRLV}} - 1 - k}{\lambda} \right) \quad k = 0, \dots, N_{\text{INTRLV}} - 1$$

where the degree λ is given in Table 22-6. The function `floor()` is a function that returns the largest integer value less than or equal to its argument value.

Table 22-6—Parameters of the interleaver

	Degree λ	Depth N_{INTRLV}
PHR	6	$10 \times 6 = 60$
PSDU	7	$7 \times 18 = 126$

The process of interleaving a subsequence is shown in Figure 22-12. The first subsequence, z^0 , shall be processed first in time and the last subsequence, z^{N_B} , shall be processed last in time.

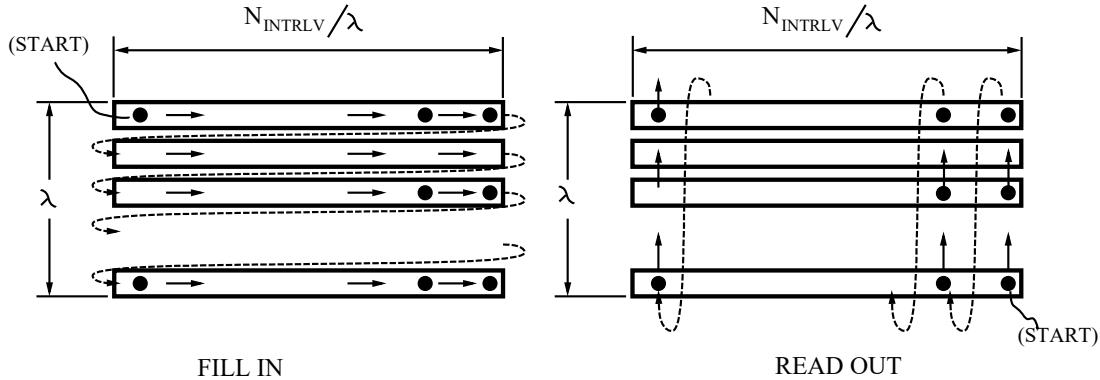


Figure 22-12—Interleaver

The deinterleaver, which performs the inverse relation, is defined by the following rule:

$$k = \lambda \times (N_{\text{INTRLV}} - 1 - i) - (N_{\text{INTRLV}} - 1) \times \text{floor}\left(\frac{\lambda \times (N_{\text{INTRLV}} - 1 - i)}{N_{\text{INTRLV}}}\right) \quad i = 0, \dots, N_{\text{INTRLV}} - 1$$

22.3.8 Bit differential encoding (BDE)

In conjunction with (N,1)-DSSS, BDE supports noncoherent detection, which is beneficial for robust operation at low-chip signal-to-noise ratio (SNR).

BDE is the modulo-2 addition of a raw bit with the previous encoded bit. This is performed by the transmitter and can be described as follows:

$$E_n = R_n \oplus E_{n-1}$$

where

- R_n is the raw bit being encoded
- E_n is the corresponding differentially encoded bit
- E_{n-1} is the previous differentially encoded bit

BDE shall be applied to the bits of the SHR field resulting in a sequence $\{E_0^{\text{SHR}}, E_1^{\text{SHR}}, \dots, E_{N_{\text{SHR}}-1}^{\text{SHR}}\}$ of differentially encoded bits, where N_{SHR} is the total number of bits in the SHR, as defined in 22.2.2.2 and 22.2.2.3. The initial state, E_{-1}^{SHR} , shall be zero.

BDE shall be applied to the 60 interleaved PHR code bits, resulting in a sequence $\{E_0^{\text{PHR}}, E_1^{\text{PHR}}, \dots, E_{59}^{\text{PHR}}\}$ of differentially encoded bits. The initial state, E_{-1}^{PHR} , is assumed to be $E_{N_{\text{SHR}}-1}^{\text{SHR}}$, assuring that during noncoherent differential detection, the very first interleaved PHR code bit can be referenced to the last SHR bit.

If differential encoding is enabled, depending on the frequency band and rate mode, as described in Table 22-4, the sequence of differentially encoded PSDU bits shall be computed as follows. Let

$R = \{R_0, R_1, \dots, R_{2N_D-1}\}$ be the sequence of interleaved PSDU code bits obtained by FEC and interleaving. The pilot spacing ratio, M , is calculated using the following:

$$M = \frac{M_p}{N}$$

where

- M_p is the pilot spacing, as described in Table 22-20
- N is the parameter of $(N, 1)$ -DSSS, as described in Table 22-4

Note that M is always an integer value. Let E_n be defined as shown:

$$E_n = \begin{cases} R_n \oplus E_{n-1}, & (n \bmod M) \neq 0 \\ R_n \oplus 0, & (n \bmod M) = 0 \end{cases}$$

generating a sequence $\{E_0^{\text{PSDU}}, E_1^{\text{PSDU}}, \dots, E_{2N_D-1}^{\text{PSDU}}\}$ of differentially encoded PSDU bits.

Referencing to zero for $(n \bmod M) = 0$ ensures that, during noncoherent differential detection, the very first interleaved PSDU code bit subsequent to a pilot sequence p , as described in 22.3.12, can be referenced to the pilot sequence.

If BDE is not applied to the PSDU, the frequency band and rate mode, as described in Table 22-4 and Table 22-5, determine whether the sequence of interleaved PSDU code bits (FEC is enabled) or the raw information PSDU bits (FEC is not enabled) remain unchanged.

22.3.9 DSSS bit-to-chip mapping

For $(N, 1)$ -DSSS, a single bit is mapped to a sequence of N binary valued chips. The number of chips, N , depends on the frequency band and rate mode, as described in Table 22-4. This mapping defines a binary (N, x) block code with $x = 1$.

Table 22-7 through Table 22-13 show $(N, 1)$ -DSSS used in the SUN O-QPSK PHY. For $N = 1$, the chip value is equal to the input bit value (no spreading).

Table 22-7—(2,1)-DSSS bit-to-chip mapping

Input bit	Chip values ($c_0 c_1$)
0	10
1	01

Table 22-8—(4,1)-DSSS bit-to-chip mapping

Input bit	Chip values ($c_0 c_1 \dots c_3$)
0	1010
1	0101

Table 22-9— $(8,1)_k$ -DSSS bit-to-chip mapping

<i>k</i>	Input bit	Chip values ($c_0 c_1 \dots c_7$)
0	0	1011 0001
	1	0100 1110
1	0	0110 0011
	1	1001 1100

Table 22-10— $(16,1)_k$ -DSSS bit-to-chip mapping

<i>k</i>	Input bit	Chip values ($c_0 c_1 \dots c_{15}$)
0	0	0010 0011 1101 0110
	1	1101 1100 0010 1001
1	0	0100 0111 1010 1100
	1	1011 1000 0101 0011

Table 22-11— $(32,1)_k$ -DSSS bit-to-chip mapping

<i>k</i>	Input bit	Chip values ($c_0 c_1 \dots c_{31}$)
0	0	1101 1110 1010 0010 0111 0000 0110 0101
	1	0010 0001 0101 1101 1000 1111 1001 1010
1	0	1110 1111 0101 0001 0011 1000 0011 0010
	1	0001 0000 1010 1110 1100 0111 1100 1101

Table 22-12— $(64,1)$ -DSSS bit-to-chip mapping

Input bit	Chip values ($c_0 c_1 \dots c_{63}$)
0	1011 0010 0010 0101 1011 0001 1101 0000
	1101 0111 0011 1101 1111 0000 0010 1010
1	0100 1101 1101 1010 0100 1110 0010 1111
	0010 1000 1100 0010 0000 1111 1101 0101

Table 22-13—(128,1)-DSSS bit-to-chip mapping

Input bit	Chip values ($c_0 c_1 \dots c_{127}$)
0	1001 1000 1000 1011 0100 1110 0100 0010
	0101 0010 0110 1101 1100 0111 1010 0000
	1101 0100 0110 0101 1101 1000 0111 0101
	1110 0111 1101 1111 1000 0000 1010 1011
1	0110 0111 0111 0100 1011 0001 1011 1101
	1010 1101 1001 0010 0011 1000 0101 1111
	0010 1011 1001 1010 0010 0111 1000 1010
	0001 1000 0010 0000 0111 1111 0101 0100

NOTE—For N greater than one, $(N,1)$ -DSSS is always preceded by differential encoding, supporting noncoherent detection of the interleaved code bits, as described in Table 22-2, Table 22-3, and Table 22-4.

For N equal to 8, 16, and 32, two spreading codes are defined, $(N,1)_0$ -DSSS and $(N,1)_1$ -DSSS. When applied to either the PHR or the PSDU, the two spreading codes are applied in an alternating manner, denoted as $(N,1)_{0/1}$ -DSSS. The even indexed bits of the PHR and PSDU, E_{2k} , for $k = 0, 1, \dots$, shall be spread with $(N,1)_0$ -DSSS and the odd indexed bits, E_{2k+1} , for $k = 0, 1, \dots$, shall be spread with $(N,1)_1$ -DSSS.

When applying $(N,4)$ -DSSS, a 4-tuple of bits is mapped to a sequence of N binary valued chips. This mapping defines a binary (N,x) block code with $x = 4$.

Table 22-14, Table 22-15, and Table 22-16 show $(N,4)$ -DSSS supported by the SUN O-QPSK PHY.

Table 22-14—(8,4)-DSSS bit-to-chip mapping

Input bits (b0 b1 b2 b3)	Chip values ($c_0 c_1 \dots c_7$)
0000	0000 0001
1000	1101 0000
0100	0110 1000
1100	1011 1001
0010	1110 0101
1010	0011 0100
0110	1000 1100
1110	0101 1101
0001	1010 0010
1001	0111 0011
0101	1100 1011
1101	0001 1010
0011	0100 0110

Table 22-14—(8,4)-DSSS bit-to-chip mapping (*continued*)

Input bits (b0 b1 b2 b3)	Chip values (c ₀ c ₁ ... c ₇)
1011	1001 0111
0111	0010 1111
1111	1111 1110

Table 22-15—(16,4)-DSSS bit-to-chip mapping

Input bits (b0 b1 b2 b3)	Chip values (c ₀ c ₁ ... c ₁₅)
0000	0011 1110 0010 0101
1000	0100 1111 1000 1001
0100	0101 0011 1110 0010
1100	1001 0100 1111 1000
0010	0010 0101 0011 1110
1010	1000 1001 0100 1111
0110	1110 0010 0101 0011
1110	1111 1000 1001 0100
0001	0110 1011 0111 0000
1001	0001 1010 1101 1100
0101	0000 0110 1011 0111
1101	1100 0001 1010 1101
0011	0111 0000 0110 1011
1011	1101 1100 0001 1010
0111	1011 0111 0000 0110
1111	1010 1101 1100 0001

Table 22-16—(32,4)-DSSS bit-to-chip mapping

Input bits (b0 b1 b2 b3)	Chip values (c ₀ c ₁ ... c ₃₁)
0000	1101 1001 1100 0011 0101 0010 0010 1110
1000	1110 1101 1001 1100 0011 0101 0010 0010
0100	0010 1110 1101 1001 1100 0011 0101 0010
1100	0010 0010 1110 1101 1001 1100 0011 0101
0010	0101 0010 0010 1110 1101 1001 1100 0011
1010	0011 0101 0010 0010 1110 1101 1001 1100
0110	1100 0011 0101 0010 0010 1110 1101 1001 1100

Table 22-16—(32,4)-DSSS bit-to-chip mapping (continued)

Input bits (b0 b1 b2 b3)	Chip values (c0 c1 ... c31)
1110	1001 1100 0011 0101 0010 0010 1110 1101
0001	1000 1100 1001 0110 0000 0111 0111 1011
1001	1011 1000 1100 1001 0110 0000 0111 0111
0101	0111 1011 1000 1100 1001 0110 0000 0111
1101	0111 0111 1011 1000 1100 1001 0110 0000
0011	0000 0111 0111 1011 1000 1100 1001 0110
1011	0110 0000 0111 0111 1011 1000 1100 1001
0111	1001 0110 0000 0111 0111 1011 1000 1100
1111	1100 1001 0110 0000 0111 0111 1011 1000

For each codeword, (c_0, \dots, c_{N-1}) , the first component, c_0 , shall be transmitted first in time, and the last component, c_{N-1} , shall be transmitted last in time.

22.3.10 MDSSS bit-to-chip mapping

The functional block diagram in Figure 22-13 is provided as a reference for specifying the MDSSS. Each bit in the PSDU shall be processed through the turbo product code (TBPC) encoding and multiplexing module. For the horizontal code of the TBPC, 3 bits are encoded into n bits with the $[n, 3]$ Hadamard code for $n = 4, 8, 16$, and 32 . The $[4, 3]$ single parity check encoder is employed as the vertical code of the TBPC.

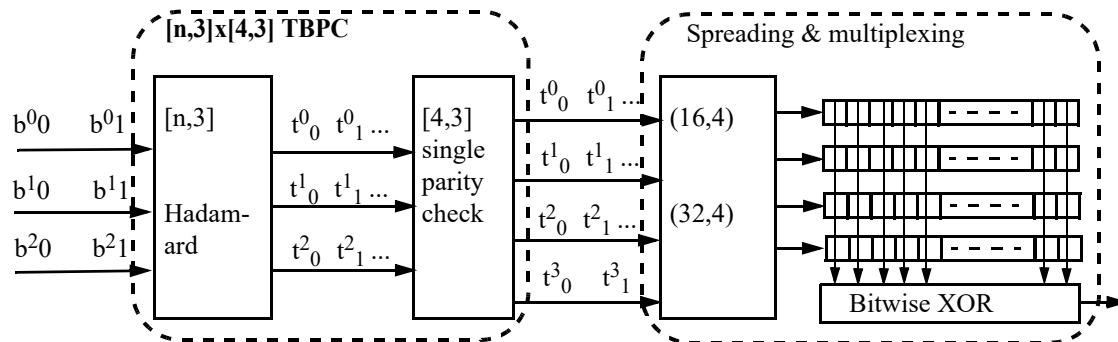


Figure 22-13—MDSSS signal flow

Each octet of the PSDU shall be mapped into three horizontal input rows, as specified in Table 22-17. The three LSBs (b^0, b^1, b^2) of each octet shall be mapped into the first horizontal input row (b^0_0, b^0_1, b^0_2), and the next three bits (b^3, b^4, b^5) of each octet shall be mapped into the second horizontal input row (b^1_0, b^1_1, b^1_2). The last horizontal input row (b^2_0, b^2_1, b^2_2) shall be mapped into the last two bits (b^6, b^7) of each octet and the reference value of the octet, which is provided by the following equation:

$$p = 0$$

Table 22-17—PSDU bit stream to horizontal code input mapping

Horizontal code input	b ⁰ 0	b ⁰ 1	b ⁰ 2	b ¹ 0	b ¹ 1	b ¹ 2	b ² 0	b ² 1	b ² 2
PSDU bit stream	Bits:0	1	2	3	4	5	6	7	p

For the horizontal coding of the TBPC, the three parallel bit streams ($b^x_0, b^x_1, b^x_2: x = 0, 1, 2$) are converted to the three parallel n -bit streams ($t^x_0, t^x_1, t^x_2, \dots, t^x_{n-1}$) through the $[n, 3]$ Hadamard encoder. An $[n, 3]$ Hadamard codeword set is given by $[h_0; h_1; h_2; h_3; h_3; h_2; h_1; h_0]$, where h_i is the i th row of the $n \times n$ Hadamard matrix and \bar{h}_i is the bitwise inversion of h_i .

For example, if $n = 4$, the $[4, 3]$ Hadamard codeword set is obtained from the (4×4) Hadamard matrix, $\bar{H}(4)$, given in the following equation, and the information bits to codeword mapping table is shown in Table 22-18.

$$\bar{H}(4) = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}$$

Table 22-18—Information bits to codeword mapping for [4,3] Hadamard encoder

Information bits (b^x_0, b^x_1, b^x_2 $(x = 0,1,2)$)	Codeword ($t^x_0, t^x_1, t^x_2, t^x_3$ $(x = 0,1,2)$)
0 0 0	0 0 0 0
0 0 1	0 1 0 1
0 1 0	0 0 1 1
0 1 1	0 1 1 0
1 0 0	1 0 0 1
1 0 1	1 1 0 0
1 1 0	1 0 1 0
1 1 1	1 1 1 1

For the vertical coding of the TBPC, the single parity check encoder adds one n -bit parity stream ($t^3_x, x = 0, 1, \dots, n - 1$) to the original three parallel n -bit streams (t^0_x, t^1_x, t^2_x). For instance, if n equals four, the single parity check encoder converts the three parallel 4-bit streams to four parallel 4-bit streams as shown:

$$T_{\text{unit}} = \begin{bmatrix} t^0_0 & t^0_1 & t^0_2 & t^0_3 \\ t^1_0 & t^1_1 & t^1_2 & t^1_3 \\ t^2_0 & t^2_1 & t^2_2 & t^2_3 \\ t^3_0 & t^3_1 & t^3_2 & t^3_3 \end{bmatrix}$$

where T_{unit} is the matrix of parallel bit streams and t^3_i , $i = 0, 1, 2, 3$ are obtained based on the following relationships:

$$\begin{aligned}t^3_0 &= \overline{t^0_0 \oplus t^1_0 \oplus t^2_0} \\t^3_1 &= \overline{t^0_1 \oplus t^1_1 \oplus t^2_1} \\t^3_2 &= \overline{t^0_2 \oplus t^1_2 \oplus t^2_2} \\t^3_3 &= \overline{t^0_3 \oplus t^1_3 \oplus t^2_3}\end{aligned}$$

As a result of [4, 3] horizontal and [4, 3] vertical coding with a parity bit per octet, the PSDU bit stream is transformed into a $[4, 3] \times [4, 3]$ TBPC codeword matrix, forming (4×4) 2-dimensional data, as shown in Figure 22-14.

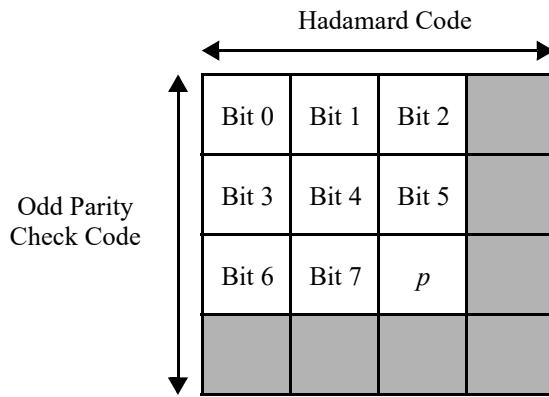


Figure 22-14—Structure of turbo product codeword

For $n = 8, 16$, and 32 , the TBPC can be generated by the serial concatenations of T_{unit} :

$$T_{[n \times 4]} = \left\{ \begin{array}{l} \left[T_{\text{unit}} \right], n = 4 \\ \left[T_{\text{unit}} \ T_{\text{unit}} \right], n = 8 \\ \left[T_{\text{unit}} \ T_{\text{unit}} \ T_{\text{unit}} \ T_{\text{unit}} \right], n = 16 \\ \left[T_{\text{unit}} \ T_{\text{unit}} \right], n = 32 \end{array} \right.$$

Each i th row of T_{unit} is spread with h_i ; i.e., the spread i th row of T_{unit} is given as follows:

$$s^i = [t^i_0 \oplus h_i \ t^i_1 \oplus h_i \ t^i_2 \oplus h_i \ t^i_3 \oplus h_i] , i = 0, 1, 2, 3$$

Then, the vertically multiplexed bit sequence \bar{c}_j of length 16 can be expressed as follows:

$$\bar{c}_j = ((s^0_j \ \& \ s^1_j) | (s^2_j \ \& \ s^3_j)) , (0 \leq j < 16)$$

$$\begin{aligned}
 \bar{c}_0 &= ((t^0_0 \& t^1_0) | (t^2_0 \& t^3_0)) \\
 \bar{c}_1 &= ((t^0_0 \& \overline{t^1_0}) | (t^2_0 \& \overline{t^3_0})) \\
 \bar{c}_2 &= ((t^0_0 \& t^1_0) | (\overline{t^2_0} \& \overline{t^3_0})) \\
 \bar{c}_3 &= ((t^0_0 \& \overline{t^1_0}) | (\overline{t^2_0} \& t^3_0)) \\
 \bar{c}_4 &= ((t^0_1 \& t^1_1) | (t^2_1 \& t^3_1)) \\
 \bar{c}_5 &= ((t^0_1 \& \overline{t^1_1}) | (t^2_1 \& \overline{t^3_1})) \\
 \bar{c}_6 &= ((t^0_1 \& t^1_1) | (\overline{t^2_1} \& \overline{t^3_1})) \\
 \bar{c}_7 &= ((t^0_1 \& \overline{t^1_1}) | (\overline{t^2_1} \& t^3_1)) \\
 \bar{c}_8 &= ((t^0_2 \& t^1_2) | (t^2_2 \& t^3_2)) \\
 \bar{c}_9 &= ((t^0_2 \& \overline{t^1_2}) | (t^2_2 \& \overline{t^3_2})) \\
 \bar{c}_{10} &= ((t^0_2 \& t^1_2) | (\overline{t^2_2} \& \overline{t^3_2})) \\
 \bar{c}_{11} &= ((t^0_2 \& \overline{t^1_2}) | (\overline{t^2_2} \& t^3_2)) \\
 \bar{c}_{12} &= ((t^0_3 \& t^1_3) | (t^2_3 \& t^3_3)) \\
 \bar{c}_{13} &= ((t^0_3 \& \overline{t^1_3}) | (t^2_3 \& \overline{t^3_3})) \\
 \bar{c}_{14} &= ((t^0_3 \& t^1_3) | (\overline{t^2_3} \& \overline{t^3_3})) \\
 \bar{c}_{15} &= ((t^0_3 \& \overline{t^1_3}) | (\overline{t^2_3} \& t^3_3))
 \end{aligned}$$

If n is greater than 4, the spread and multiplexed bit sequence \bar{c}_j of $T_{[n \times 4]}$ can also be expressed as the repeated form of the preceding equation.

Then, the final output bit stream shall be bitwise XORed by covering code for the chip and symbol synchronization. For each of (16,8), (32,8), (64,8), (128,8) MDSSS, the covering code shall be bit 0 of (16,1)₀-DSSS, (32,1)₀-DSSS, (64,1)-DSSS, (128,1)-DSSS code, which are described in Table 22-10, Table 22-11, Table 22-12, and Table 22-13, respectively.

The final output chip sequence, $c_0 \sim c_{4n-1}$ ($n = 4, 8, 16, 32$), of (n,8) MDSSS shall be described as follows:

$$c_i = \bar{c}_{\left((i \bmod 4) + \lfloor \frac{i}{n} \rfloor \times 4\right)} \oplus m_i, (0 \leq i < 4n)$$

where m_i is the covering code.

22.3.11 Chip whitening

When the spreading mode is set to DSSS, the PSDU chip sequence shall be whitened, depending on the frequency band and rate mode, as shown in Table 22-19. This improves spectral properties of modes with low spreading gain or insufficient spectral properties (i.e., notches) of the spreading codes. For all other modes, no chip whitening shall be applied.

Table 22-19—Chip whitening for DSSS

Band designation (MHz)	Chip rate (kchip/s)	Rate mode
470	100	1 and 2 and 3
780	100	1 and 2 and 3
	1000	2 and 3
866	100	1 and 2 and 3
867	100	1 and 2 and 3
868	100	1 and 2 and 3
870	100	1 and 2 and 3
915	100	1 and 2 and 3
	1000	2 and 3
915-a	100	1 and 2 and 3
	1000	2 and 3
915-b	100	1 and 2 and 3
	1000	2 and 3
915-c	100	2 and 3
915-d	100	1 and 2 and 3
915-e	100	1 and 2 and 3
917	100	1 and 2 and 3
	1000	2 and 3
919	100	1 and 2 and 3
920	100	1 and 2 and 3
920-a	100	1 and 2 and 3
920-b	100	1 and 2 and 3
2450	2000	3

Chip whitening is the modulo-2 addition of a chip of the PSDU at the output of the bit-to-chip mapper with the value of a cyclic m -sequence $S_{(k \bmod (2^m - 1))}$ of length $m = 9$. This shall be performed by the transmitter and is described as follows:

$$c'_k = c_k \oplus S_{(k \bmod 511)}$$

where

c_k is the raw PSDU chip being whitened

c'_k is the whitened chip

Index k starts at 0, referring to the first chip of the PSDU at the output of the bit-to-chip mapper and is increased by one at every chip interval. Figure 22-15 shows the whitening process. At $k = 0$, the register shall be initialized as follows:

$$(u_{k-1}, u_{k-2}, \dots, u_{k-9}) = (1, 0, 0, 0, 0, 0, 0, 0, 0)$$

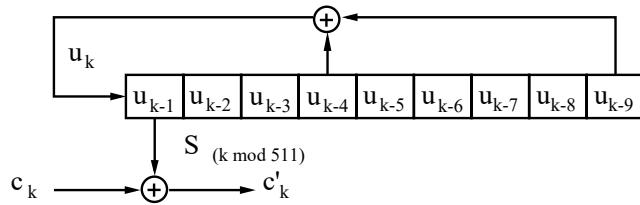


Figure 22-15—Chip whitening

22.3.12 Pilot insertion

Periodic insertion of known chip sequences (pilots) into the stream of PSDU chips shall be used to simplify symbol time, channel or phase tracking during receive, taking the finite coherence time of the radio channel into account. The pilot structure of this PHY is shown in Figure 22-16.

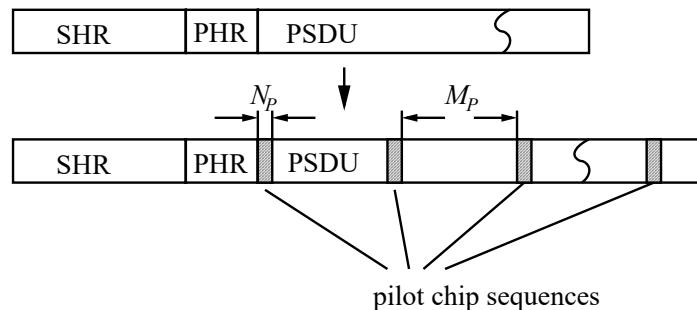


Figure 22-16—PSDU pilot insertion

Since the extended PSDU chip sequence always starts with a first pilot sequence, the complexity of PHR decoding can be also reduced.

The pilot length N_P (in number of chip samples), the pilot spacing M_P (in number of chip samples), and the pilot sequence $p = (p_0, p_1, \dots, p_{N_P-1})$ depend on the frequency band and are shown in Table 22-20.

Table 22-20—Pilot length, spacing, and chip sequences

Band designation (MHz)	Length N_p (# of chips)	Spacing M_p (# of chips)	Chip sequence $p = (p_0, p_1, \dots, p_{N_P-1})$
470	32	512	1101 1110 1010 0010 0111 0000 0110 0101
	32	512	1101 1110 1010 0010 0111 0000 0110 0101
	64	1024	1011 0010 0010 0101 1011 0001 1101 0000 1101 0111 0011 1101 1111 0000 0010 1010

Table 22-20—Pilot length, spacing, and chip sequences (*continued*)

Band designation (MHz)	Length N_p (# of chips)	Spacing M_p (# of chips)	Chip sequence $p = (p_0, p_1, \dots, p_{N_p-1})$
866	32	512	1101 1110 1010 0010 0111 0000 0110 0101
867	32	512	1101 1110 1010 0010 0111 0000 0110 0101
868	32	512	1101 1110 1010 0010 0111 0000 0110 0101
870	32	512	1101 1110 1010 0010 0111 0000 0110 0101
915	32	512	1101 1110 1010 0010 0111 0000 0110 0101
	64	1024	1011 0010 0010 0101 1011 0001 1101 0000 1101 0111 0011 1101 1111 0000 0010 1010
915-a	32	512	1101 1110 1010 0010 0111 0000 0110 0101
	64	1024	1011 0010 0010 0101 1011 0001 1101 0000 1101 0111 0011 1101 1111 0000 0010 1010
915-b	32	512	1101 1110 1010 0010 0111 0000 0110 0101
	64	1024	1011 0010 0010 0101 1011 0001 1101 0000 1101 0111 0011 1101 1111 0000 0010 1010
915-c	32	512	1101 1110 1010 0010 0111 0000 0110 0101
	64	1024	1011 0010 0010 0101 1011 0001 1101 0000 1101 0111 0011 1101 1111 0000 0010 1010
915-d	32	512	1101 1110 1010 0010 0111 0000 0110 0101
915-e	32	512	1101 1110 1010 0010 0111 0000 0110 0101
917	32	512	1101 1110 1010 0010 0111 0000 0110 0101
	64	1024	1011 0010 0010 0101 1011 0001 1101 0000 1101 0111 0011 1101 1111 0000 0010 1010
919	32	512	1101 1110 1010 0010 0111 0000 0110 0101
920	32	512	1101 1110 1010 0010 0111 0000 0110 0101
920-a	32	512	1101 1110 1010 0010 0111 0000 0110 0101
920-b	32	512	1101 1110 1010 0010 0111 0000 0110 0101
2450	128	2048	1001 1000 1000 1011 0100 1110 0100 0010 0101 0010 0110 1101 1100 0111 1010 0000 1101 0100 0110 0111 1101 1000 0111 0101 1110 0111 1101 1111 1000 0000 1010 1011

Let:

$$u = \{u_0, u_1, \dots, u_{N_{\text{PSDU}}-1}\}$$

be the sequence of PSDU chips prior to pilot insertion, assuming the first PSDU chip sample, u_0 , is transmitted first in time, and the last PSDU chip sample, $u_{N_{\text{PSDU}} - 1}$, is transmitted last in time. The number N_{PSDU} can be computed as follows:

$$N_{\text{PSDU}}(\text{LENGTH}) = \begin{cases} R_{\text{spread}} \times 2 \times N_D(\text{LENGTH}), & \text{if FEC is enabled} \\ R_{\text{spread}} \times 8 \times \text{LENGTH}, & \text{if FEC is disabled} \end{cases}$$

where

LENGTH is the number of octets in the PSDU

R_{spread} is the spreading rate, i.e., the ratio of number of output chips N to number of input bits x for (N, x) bit-to-chip mapping, as described in Table 22-4 and Table 22-5

N_D is the number of uncoded bits, as defined in 22.3.6

Let L as a function of the variable LENGTH be defined as follows:

$$L(\text{LENGTH}) = \text{ceiling}\left(\frac{N_{\text{PSDU}}(\text{LENGTH})}{M_P}\right)$$

Let u^j be the following subsequences:

$$u^j = \begin{cases} \{u_{jM_p}, u_{jM_p+1}, \dots, u_{(j+1)M_p-1}\} & \text{if } (j+1)M_p \leq N_{\text{PSDU}} \\ \{u_{jM_p}, u_{jM_p+1}, \dots, u_{N_{\text{PSDU}}-1}\} & \text{if } (j+1)M_p > N_{\text{PSDU}} \end{cases} \quad \text{for } j = 0, \dots, L-1$$

The pilot extended PSDU chip sequence is as follows:

$$c_{\text{PSDU}} = \{p, u^0, \dots, p, u^{L-1}\}$$

22.3.13 Modulation parameters for O-QPSK

A chip value shall be mapped into a binary real-valued symbol out of $\{-1, 1\}$ as follows:

$$\zeta(c) = \begin{cases} -1, & c = 0 \\ 1, & c = 1 \end{cases}$$

The half-sine pulse shape is used to represent each baseband chip and is as follows:

$$p(t) = \begin{cases} \sin\left(\frac{\pi t}{2T_c}\right), & \text{for } 0 \leq t \leq 2T_c \\ 0, & \text{otherwise} \end{cases}$$

where the chip duration T_c is the inverse of the chip rate, as described in Table 22-4 and Table 22-5.

For some geographic regional regulation may require tighter spectral emission. For these regions a raised cosine pulse shape with roll-off factor of $r = 0.8$ should be used to represent each baseband symbol and is described as follows:

$$p(t) = \begin{cases} \frac{\sin(\pi t/T_c)}{\pi t/T_c} \times \frac{\cos(r\pi t/T_c)}{1 - 4r^2 t^2/T_c^2}, & t \neq 0 \\ 1, & t = 0 \end{cases}$$

Let $c_{PPDU} = \{c_k\}_{0}^{N_{PPDU}-1}$ be the discrete-time sequence of consecutive chip samples of the PPDU, where the first sample, c_0 , is transmitted first in time and the last sample, $c_{N_{PPDU}-1}$, is transmitted last in time. The continuous-time, pulse-shaped complex baseband signal is as follows:

$$y(t) = \sum_{k=0}^{N_{PPDU}/2-1} \zeta(c_{2k})p(t-2kT_c) + j\zeta(c_{2k+1})p(t-(2k+1)T_c)$$

with $j = \sqrt{-1}$.

22.4 Support of legacy devices of the 780 MHz, 915 MHz, and 2450 MHz O-QPSK PHYs

When operating in the 779–787 MHz frequency band, a compliant device of the SUN O-QPSK PHY shall be able to communicate with devices of the 780 MHz band O-QPSK PHY within the specifications given in Clause 13.

When operating in the 902–928 MHz frequency band, a compliant device of the SUN O-QPSK PHY shall be able to communicate with devices of the 915 MHz band O-QPSK PHY within the specifications given in Clause 13.

When operating in the 2400–2483.5 MHz frequency band, a compliant device of the SUN O-QPSK PHY shall be able to communicate with devices of the 2450 MHz band O-QPSK PHY within the specifications given in Clause 13.

22.5 SUN O-QPSK PHY RF requirements

22.5.1 Operating frequency range

The SUN O-QPSK PHY operates in the following bands:

- 470–510 MHz
- 779–787 MHz
- 865–868 MHz
- 866–869 MHz
- 868–870 MHz
- 870–876 MHz
- 902–928 MHz
- 902–928 (alternate) MHz
- 902–907.5 MHz and 915–928 MHz

- 915–928 MHz
- 915–921 MHz
- 915–918 MHz
- 917–923.5 MHz
- 919–923 MHz
- 920–928 MHz
- 920.5–924.5 MHz
- 920–925 MHz
- 2400–2483.5 MHz

22.5.2 Transmit power spectral density (PSD) mask

The SUN O-QPSK transmit PSD mask shall conform with local regulations.

22.5.3 Receiver sensitivity

Under the conditions specified in 11.1.8, a compliant device shall be capable of achieving the sensitivity values given in Table 22-21 and Table 22-22 or better.

Table 22-21—Required receiver sensitivity for spreading mode DSSS [dBm]

Band designation (MHz)	Chip rate (kchip/s)	Rate mode			
		0	1	2	3
470	100	−110	−105	−100	−95
780	100	−110	−105	−100	−95
	1000	−105	−100	−95	−90
866	100	−110	−105	−100	−95
867	100	−110	−105	−100	−95
868	100	−110	−105	−100	−95
870	100	−110	−105	−100	−95
915	100	−110	−105	−100	−95
	1000	−105	−100	−95	−90
915-a	100	−110	−105	−100	−95
	1000	−105	−100	−95	−90
915-b	100	−110	−105	−100	−95
	1000	−105	−100	−95	−90
915-c	100	−110	−105	−100	−95
	1000	−105	−100	−95	−90
915-d	100	−110	−105	−100	−95
915-e	100	−110	−105	−100	−95

Table 22-21—Required receiver sensitivity for spreading mode DSSS [dBm] (continued)

Band designation (MHz)	Chip rate (kchip/s)	Rate mode			
		0	1	2	3
917	100	-110	-105	-100	-95
	1000	-105	-100	-95	-90
919	100	-110	-105	-100	-95
920	100	-110	-105	-100	-95
920-a	100	-110	-105	-100	-95
920-b	100	-110	-105	-100	-95
2450	2000	-105	-100	-95	-90

Table 22-22—Required receiver sensitivity for spreading mode MDSSS [dBm]

Band designation (MHz)	Rate mode			
	0	1	2	3
470	not supported			
780	-105	-100	-95	-90
866	not supported			
867	not supported			
868	not supported			
870	not supported			
915	-105	-100	-95	-90
915-a	-105	-100	-95	-90
915-b	-105	-100	-95	-90
915-c	-105	-100	-95	-90
915-d	not supported			
915-e	not supported			
917	-105	-100	-95	-90
919	not supported			
920	not supported			
920-a	not supported			
920-b	not supported			
2450	-105	-100	-95	-90

22.5.4 Adjacent channel rejection

The interference-to-signal ratio (ISR) is the ratio of the signal power of an interferer relative to the signal power of the desired signal. The adjacent channel rejection shall be measured as follows: the desired signal shall be a SUN O-QPSK compliant signal of pseudo-random PSDU data. For a given rate mode, the desired signal is input to the receiver at a level 3 dB above the maximum allowed receiver sensitivity of Table 22-21 and Table 22-22.

The interfering signal shall be a SUN O-QPSK compliant signal with the following characteristics:

- Pseudo-random PSDU
- Spreading mode set to either DSSS or MDSSS
- The same chip rate as the desired signal
- Chip-whitening enabled

The interferer is separated in frequency by $|\Delta f|$ from the carrier frequency of the desired channel with an ISR, as shown in Table 22-23. The test shall be performed for only one interfering signal at a time. The receiver shall meet the error rate criteria defined in 11.1.8 under these conditions.

**Table 22-23—Minimum interference-to-signal ratio (ISR)
requirements depending on $|\Delta f|$**

Band designation (MHz)	Chip rate (kchip/s)	$ \Delta f $ (MHz)	ISR (dB)
470	100	0.4	10
		0.8	30
780	100	0.4	10
		0.8	30
	1000	2	10
		4	30
866	100	0.2	10
		1.4	30
867	100	0.2	10
		0.4	30
868	100	0.65	10
		1.225	30
870	100	0.2	10
		0.4	30
915	100	0.4	10
		0.8	30
	1000	2.0	10
		4.0	30

**Table 22-23—Minimum interference-to-signal ratio (ISR)
requirements depending on $|\Delta f|$ (continued)**

Band designation (MHz)	Chip rate (kchip/s)	Δf (MHz)	ISR (dB)
915-a	100	0.4	10
		0.8	30
	1000	2	10
		4	30
915-b	100	0.4	10
		0.8	30
	1000	2	10
		4	30
915-c	100	0.4	10
		0.8	30
	1000	2	10
		4	30
915-d	100	0.2	10
		0.4	30
915-e	100	0.2	10
		0.4	30
917	100	0.4	10
		0.8	30
	1000	0.2	10
		0.4	30
919	100	0.2	10
		0.4	30
920	100	0.2	10
		0.4	30
920-a	100	0.2	10
		0.4	30
920-b	100	0.2	10
		0.4	30
2450	2000	5.0	10.0
		10.0	30

22.5.5 TX-to-RX turnaround time

The SUN O-QPSK PHY shall meet the requirements for TX-to-RX turnaround time as defined in 11.2.2.

22.5.6 RX-to-TX turnaround time

The SUN O-QPSK PHY shall meet the requirements for RX-to-TX turnaround time as defined in 11.2.3.

22.5.7 EVM definition

A transmitter shall have EVM values of less than 35% when measured for 1000 chips. The EVM measurement shall conform with 11.2.4.

22.5.8 Transmit center frequency and symbol tolerance

The transmit center frequency tolerance shall be $\pm 20 \times 10^{-6}$ maximum. When communicating with legacy devices, as described in 22.4, the receiver shall be capable of receiving signals with a center frequency offset tolerance of up to $\pm 40 \times 10^{-6}$.

The symbol clock frequency tolerance shall be $\pm 20 \times 10^{-6}$ maximum. When communicating with legacy devices, as described in 22.4, the receiver shall be capable of receiving signals with a symbol clock frequency tolerance of up to $\pm 40 \times 10^{-6}$.

The transmit center frequency and the symbol clock frequency shall be derived from the same reference oscillator.

22.5.9 Transmit power

A transmitter shall be capable of transmitting at least -3 dBm. Devices should transmit lower power when possible in order to reduce interference to other devices and systems.

The maximum transmit power is limited by local regulatory bodies.

22.5.10 Receiver maximum input level of desired signal

The SUN O-QPSK PHY shall have a receiver maximum input level greater than or equal to -20 dBm using the measurement defined in 11.2.5.

22.5.11 Receiver ED

The SUN O-QPSK PHY shall provide the receiver ED measurement as described in 11.2.6.

22.5.12 LQI

The SUN O-QPSK PHY shall provide the LQI measurement as described in 11.2.7.

22.5.13 CCA

The detection time, *phyCcaDuration* (as defined in 12.2), for CCA is shown in Table 22-24; see 11.2.8 for information on the 920 MHz band. The ED threshold shall correspond to a received signal power of at most -90 dBm, when applying CCA Mode 1 or CCA Mode 3, as defined in 11.2.8.

Table 22-24—CCA duration for SUN O-QPSK PHY

Band designation (MHz)	Chip rate (kbp/s)	<i>phyCcaDuration</i> (# of symbols)
470	100	4
780	100	4
	1000	8
866	100	4
867	100	4
868	100	4
870	100	4
915	100	4
	1000	8
915-a	100	4
	1000	8
915-b	100	4
	1000	8
915-c	100	4
	1000	8
915-d	100	4
915-e	100	4
917	100	4
	1000	8
919	100	4
920-a	100	4
920-b	100	4
2450	2000	8

23. LECIM DSSS PHYS

23.1 PPDU format for DSSS

The PSDU field carries the data of the PPDU. The size of the field is set by the value of *phyLecimDsssPsduSize*. The composition of the PSDU field is affected by the optional use of tail biting, as described in 23.2.4. The PPDU shall be formatted as illustrated in Figure 23-1.

Octets: 0/2/4	0/1	16/24/32
Preamble	SFD	PSDU
SHR		PHY payload

Figure 23-1—Format of the LECIM DSSS PPDU

The Preamble field length may be selected via *phyLecimDsssPreambleSize*. The SFD values and LECIM DSSS preamble values are given in Table 23-1.

Table 23-1—LECIM DSSS preamble and SFD values

<i>phyLecimDsssPreambleSize</i>	Preamble field	SFD field (if <i>phyLecimDsssSfdPresent</i> is TRUE)
0	Not present	Not present
16	0011 1111 0101 1001	0011 1000
32	0000 1111 1101 1011 0110 0111 0010 1010	1000 0100

The SFD field, if present, indicates the beginning of the frame. One SFD is used when the preamble length is 2 octets, and a second SFD is used when the preamble length is 4 octets. Both SFDs are given in Table 23-1.

For the purposes of calculating the Ack frame timing required in 6.6.4, the default length of the Preamble size shall be 4 octets.

23.2 Modulation and spreading

23.2.1 General

In this subclause, modulation symbol refers to the output of the BPSK/O-QPSK modulator, as shown in Figure 23-2.

23.2.2 Data rate

The information data rate depends on the band in use, the spreading factor, the modulation rate, and the modulation being used, and it is calculated, in kilobits per second, as follows:

$$\text{DataRate} = 0.5 \times \frac{(\text{phyLecimDsssPpduModulationRate} \times \text{ChipPerSymbol})}{\text{phyLecimDsssPsduSpreadingFactor}}$$

where $ChipPerSymbol = 1$ when BPSK modulation is used and $ChipPerSymbol = 2$ when O-QPSK modulation is used. The term 0.5 represents the FEC $\frac{1}{2}$ coding.

23.2.3 Reference modulator diagram

The functional block diagram in Figure 23-2 is provided as a reference for specifying the LECIM DSSS PHY modulation. All binary data contained in the SHR and PSDU shall be encoded using the modulation shown in Figure 23-2.

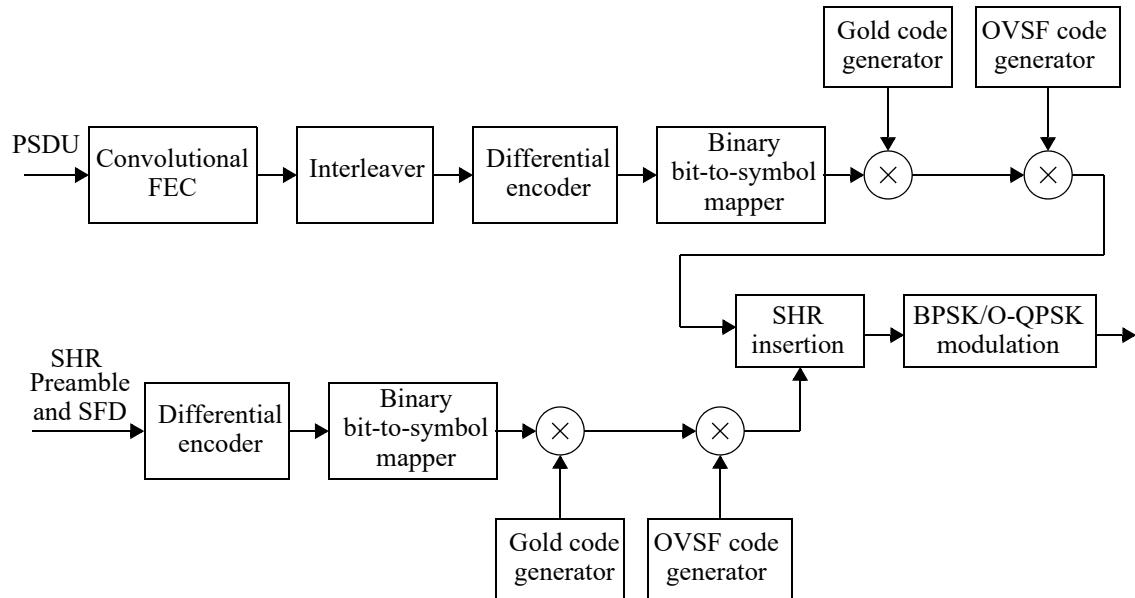


Figure 23-2—LECIM DSSS reference modulator diagram

23.2.4 Convolutional FEC encoding

FEC shall employ rate 1/2 convolutional coding with constraint length $k = 7$. The encoder is shown in Figure 23-3, where \oplus denotes modulo-2 addition.

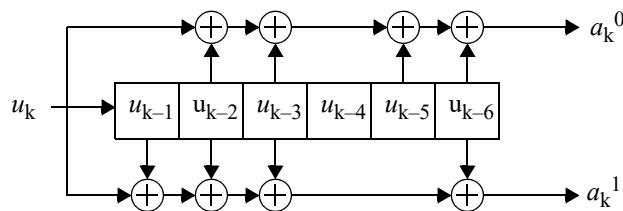


Figure 23-3—LECIM DSSS PHY convolutional encoder

Tail biting may optionally be employed. When $phyLecimDsssFecTailBitingEnabled$ is set to TRUE, the possible sizes of the PSDU are as defined in Figure 23-1 and the initial encoder state at $k = 0$ shall be set to the last six bits of the PSDU.

When $phyLecimDsssFecTailBitingEnabled$ is set to FALSE, the initial encoder state at $k = 0$ shall be set to $(u_{-1}, u_{-2}, \dots, u_{-6}) = (0, 0, 0, 0, 0, 0)$. The size of the PSDU is reduced by one octet, and the PSDU shall be

extended to equal one of the possible sizes defined in Figure 23-1 by appending a termination sequence of eight bits, all zero.

23.2.5 Interleaver

23.2.5.1 General

The output of the convolutional encoder is interleaved using a pruned bit reversal interleaving algorithm.

The text that follows contains examples of bit reversal interleavers for three PSDU sizes (256, 384, and 512 bits). PSDU sizes that are not powers of two (e.g., 384) employ pruning.

23.2.5.2 256-bit fragment size

If the input sequence into the interleaver is represented by:

$$[S_0 \ S_1 \dots S_{255}]$$

then the output sequence of the interleaver can be described as follows:

$$[S_0 \ S_N \ \dots \ S_{255}]$$

The value N for the M^{th} output is determined as the bit-reversal of the value M .

Representing the value M as a binary representation:

$$M = [m_7 \ m_6 \ \dots \ m_0]$$

where m_i are the binary digits, then:

$$N = [m_0 \ m_1 \ \dots \ m_7]$$

where M is incremented sequentially from 0 to 255.

For example, if $M = 1 = 0000\ 0001_2$, then $N = 1000\ 0000_2 = 128$.

23.2.5.3 384-bit fragment size

If the input sequence into the interleaver is represented by:

$$[S_0 \ S_1 \ \dots \ S_{383}]$$

then the output sequence of the interleaver can be described as follows:

$$[S_0 \ S_N \ \dots \ S_{383}]$$

The value N for the M_{th} output is determined as the bit-reversal of the value M .

Representing the value M as a binary representation:

$$M = [m_8 \ m_7 \ \dots \ m_0]$$

where m_i are the binary digits, then:

$$N = [m_0 \ m_1 \dots m_8]$$

where M is incremented sequentially from 0 to 511 and M' are the ordered set of M whose corresponding N is less than 384. (This is the pruning process.)

For example:

- If $M = 1 = 00000\ 0001_2$, then $N = 10000\ 0000_2 = 256$.
- If $M = 2 = 00000\ 0010_2$, then $N = 01000\ 0000_2 = 128$.
- If $M = 3 = 00000\ 0011_2$, then $N = 11000\ 0000_2 = 384$, and since it is not less than 384, it would not be included in the ordered set M' (i.e., it is pruned from the result).
- If $M = 4 = 00000\ 0100_2$, then $N = 00100\ 0000_2 = 64$.

An example is given in “Examples of IEEE Std 802.15.4 PHY encodings” [B10].

23.2.5.4 512-bit fragment size

If the input sequence into the interleaver is represented by:

$$[S_0 \ S_1 \dots S_{511}]$$

then the output sequence of the interleaver can be described as follows:

$$[S_0 \ S_N \ \dots \ S_{511}]$$

The value N for the M^{th} output is determined as the bit-reversal of the value M .

Representing the value M as a binary representation:

$$M = [m_8 \ m_7 \dots m_0]$$

where m_i are the binary digits, then:

$$N = [m_0 \ m_1 \dots m_8]$$

where M is incremented sequentially from 0 to 511.

For example, if $M = 1 = 00000\ 0001_2$, then $N = 10000\ 0000_2 = 256$.

23.2.6 Differential encoding

The differential encoding of the DSSS PHY is described in 14.2.4.

23.2.7 Bit-to-symbol and symbol-to-chip encoding

23.2.7.1 General

Each input bit shall be mapped to a binary symbol as follows:

$$x[n] = \begin{cases} 1, & \text{if } b[n] = 0 \\ -1, & \text{if } b[n] = 1 \end{cases}$$

These binary symbols shall be spread to chip-rate with SF. This process is illustrated in Figure 23-4 for SF = 8. The symbols are first up-sampled SF times and interpolated using a scaled boxcar filter, as shown in Figure 23-5, i.e., the symbol is repeated SF times at chip-rate.

NOTE—This is a mathematical representation of the direct sequence spreading operation. This process can be implemented in an alternative manner that is mathematically equivalent.

The up-sampled symbols are multiplied by a specified Gold code to create the spread signal.

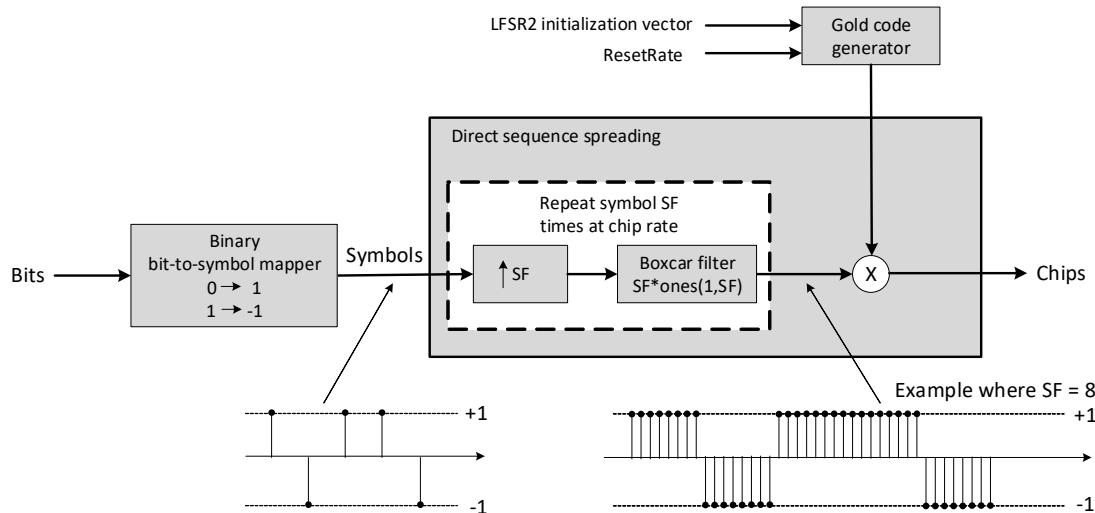


Figure 23-4—Bit-to-chip diagram for LECIM DSSS PHY

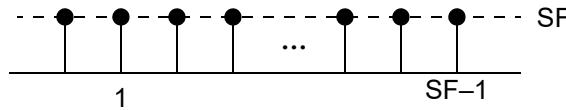


Figure 23-5—Boxcar filter

23.2.7.2 Gold code generator

Gold code sequences are a large family of easily parameterized PN sequences with good periodic cross-correlation and off-peak auto-correlation properties. A Gold code sequence is derived from the binary addition (XOR) of two maximum length sequences (*m*-sequences, or MLS). The *m*-sequences are generated using Fibonacci LFSR. Each LFSR is constructed from primitive (or prime) polynomials over Galois field 2 (GF[2]). The resulting sequences thus constitute segments of a set of Gold sequences. The Gold sequence can be parameterized by setting the initialization vector of LFSR2 to different values (LFSR1 is always initialized to 0x1).

- $m = 25$ (length of LFSR)
- $n = 2^m - 1 = 33\ 554\ 431$ (length of Gold code)
- $n + 2 = 33\ 554\ 433$ (total Gold sequences) = $a, b, a \times b, a \times Tb, a \times T2b, \dots$

LFSR (MLS) generator polynomials:

- $p1(x) = x^{25} + x^3 + 1$
- $p2(x) = x^{25} + x^3 + x^2 + x + 1$

23.2.7.3 Orthogonal variable spreading factor (OVSF) code generator

The OVSF code is the same as the Walsh code, except that each sequence has a different index number in the code set, which results from their different generator algorithms.

In a LECIM system, a Gold code shall be used inside a co-located orthogonal network as the primary code. An OVSF code is optionally used to identify the co-located orthogonal networks and clusters in order to provide double protection from outside interference.

The OVSF code is defined recursively by a tree structure, as shown in Figure 23-6.

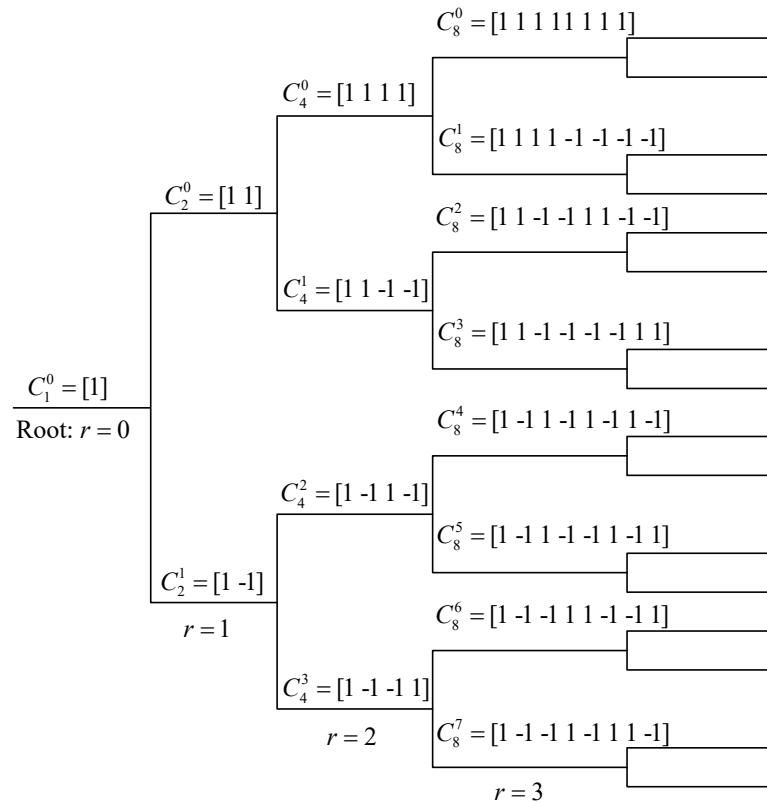


Figure 23-6—OVSF code tree

The OVSF code generator block outputs may be specified by two parameters in the mask of the block: the SF and the code index. In Figure 23-6, C_N^i is a code of length $N = 2^r$ at depth r in the tree. The code index i has the range $\{0, 1, \dots, N-1\}$, which specifies how far down the column of the tree at depth r the code appears. The root code C_1^0 has length $N = 1$, code index $i = 0$, and depth $r = 0$. Two branches of

length 2^{r+1} leading out of C_N^i are labeled by the sequences $[C_N^i C_N^i]$ and $[C_N^i \bar{C}_N^i]$, where $\bar{C}_N^i = -C_N^i$.

To recover the code from the SF and the code index, the following procedure is applied. Convert the code index i into binary form. If $i < N-1$, add zeros to the left side of this binary code index in order to make it have the N -bits form. To choose the specific code in the tree, the path is determined using the binary path sequence of the form $x = [x_1, x_2, \dots, x_r]$. This binary path sequence describes the path from the root to the specific code, according to the following rule: the path takes the upper branch from the code at depth r' if $x_{r'} = 0$, or the lower branch if $x_{r'} = 1$ for $1 \leq r' \leq r$. For example, with the root $C_i^0 = [1]$ and $r = \log_2 N$ of C_N^i , then C_{2N}^{2i} and C_{2N}^{2i+1} are defined as follows:

$$C_{2N}^{2i} = [C_N^i C_N^i] \text{ if } x_{r+1} = 0 \text{ and } C_{2N}^{2i+1} = [C_N^i \bar{C}_N^i] \text{ if } x_{r+1} = 1.$$

To make the just described procedure more clear, a specific example is given. Assuming the code has SF $N = 16$ and code index $i = 6$, the steps are as follows:

- a) Convert $i = 6$ to the binary number 110.
- b) Add one 0 to the left to obtain 0110, which has length $r = \log_2 16 = 4$.
- c) Construct the sequences C_N^i according to Table 23-2.

From Table 23-2, code C_{16}^6 has SF $N = 16$ and code index $i = 6$.

Table 23-2—Example of OVSF code recovery

Path depth r	Path sequence x_r	Code index i	Code C_N^i
0		0	$C_1^0 = [1]$
1	0	0	$C_2^0 = [C_1^0 C_1^0] = [1][1]$
2	1	1	$C_4^1 = [C_2^0 \bar{C}_2^0] = [1 1][-1 -1]$
3	1	3	$C_8^3 = [C_4^1 \bar{C}_4^1] = [1 1 -1 -1][-1 -1 1 1]$
4	0	6	$C_{16}^6 = [C_8^3 C_8^3] = [1 1 -1 -1 -1 -1 1 1][1 1 -1 -1 -1 -1 1 1]$

The logical level architecture of the OVSF code generator is shown in Figure 23-7. There are two inputs for the OVSF code generator: an OVSF code index i and SF N . The code index i is stored in the N -bit binary representation as $(V_{N-1} V_{N-2} \dots V_1 V_0)$. According to the input SF N , the chip rate binary counter counts incrementally from 0 to $N-1$ in the N -bit binary representation as $(b_{N-1} b_{N-2} \dots b_1 b_0)$.

For example, to generate the code C_8^5 in Figure 23-6, considering the digital CMOS logic operation, the mapping $\{"+1"\rightarrow\text{"logic 0"}\}$ and $\{"-1"\rightarrow\text{"logic 1"}\}$ is specified. The participation of the specific bits in the XOR operation according to the OVSF code index i is periodic in time and can be controlled by the chip rate binary counter, as illustrated in Figure 23-8 and Table 23-3.

The OVSF code output is specified by *phyLecimDsssPsduOvsfSpreadingFactor* and *phyLecimDsssPsduOvsfCodeIndex*. The same values shall be used to recover the OVSF code.

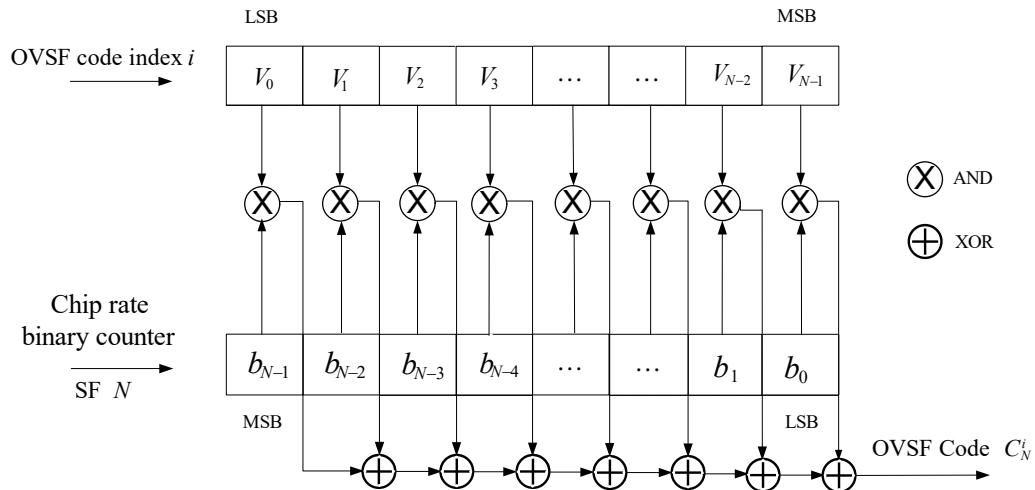


Figure 23-7—Logical level

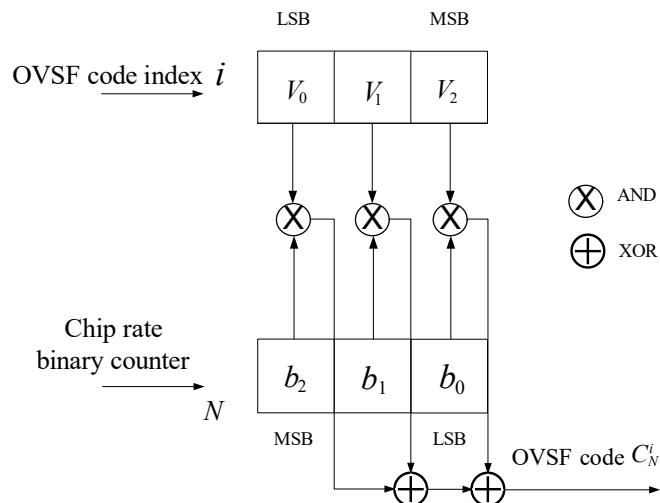


Figure 23-8—An example of OVSF code generator for LECIM DSSS PHY

Table 23-3—Example of OVSF code output

Chip rate counter $b_2\ b_1\ b_0$	Operation $V_0\ V_1\ V_2$ with code index $i = 5$	OVSF code output C_8^5	
		CMOS logic mapping form	Form in Figure 23-6
0 0 0	0	0	1
0 0 1	V_2	1	-1
0 1 0	V_1	0	1
0 1 1	$V_1 \oplus V_2$	1	-1
1 0 0	V_0	1	-1

Table 23-3—Example of OVSF code output (*continued*)

Chip rate counter b2 b1 b0	Operation $V_0 V_1 V_2$ with code index $i = 5$	OVSF code output C_8^5	
		CMOS logic mapping form	Form in Figure 23-6
1 0 1	$V_0 \oplus V_2$	0	1
1 1 0	$V_0 \oplus V_1$	1	-1
1 1 1	$V_0 \oplus V_1 \oplus V_2$	0	1

23.2.8 BPSK/O-QPSK modulation

23.2.8.1 BPSK modulation

BPSK modulation for the DSSS PHY is described in 14.2.6.

The chip sequences are modulated onto the carrier using BPSK with pulse shaping. A chip value of one corresponds to a positive pulse and a chip value of zero corresponds to a negative pulse.

Chip rates/bands are shown in Table 11-2.

During each symbol period, chip C_0 is transmitted first and C_{SF-1} is transmitted last.

23.2.8.2 O-QPSK modulation

The chip sequences representing each data symbol are modulated onto the carrier using offset quadrature phase-shift keying (O-QPSK). Even-indexed chips are modulated onto the in-phase (I) carrier, and odd-indexed chips are modulated onto the quadrature-phase (Q) carrier. To form the offset between I-phase and Q-phase chip modulation, the Q-phase chips shall be delayed by T_c with respect to the I-phase chips, as illustrated in Figure 23-9, where T_c is the inverse of the chip rate and SF is *phyLecimDsssPsduSpreadingFactor*.

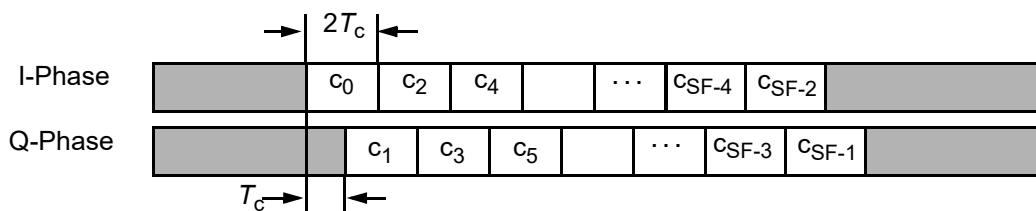


Figure 23-9—O-QPSK chip modulation

23.3 PSDU fragmentation

23.3.1 General

The LECIM DSSS PHY includes a fragmentation sublayer that divides the PSDU into a sequence of fragments. The synchronization and PHY header are prepended onto each fragment and a FICS is appended resulting in the PPDU. The FICS allows the recipient device to discard invalid PPDUs and the Frak provides

for retransmission of only the discarded PPDUs. The recipient device's fragmentation sublayer reassembles the fragments into the original PSDU and passes it to the MAC for its processing.

Devices that support the LECIM DSSS PHY shall support PSDU fragmentation. When *phyPsduFragEnabled* is TRUE, the MPDU is processed into a sequence of fragments.

23.3.2 Configuration

To reduce the fragment packet overhead, both the initiating device and the recipient device shall be configured prior to the transmission of the fragment sequence. The configuration consists of the initiating device sending a Data frame containing solely one FSCD IE as described in 10.15.2.1, to the recipient. The configuration information, identified by its TID, shall be used by the recipient device to process the received fragments identified with the same TID and reassemble them into the PSDU.

The Data frame containing the FSCD IE shall be transmitted with the AR field set to one. If an acknowledgment is received, the initiating device shall transmit the fragments until either the transaction is complete or the transmission is aborted. A TID field value of zero in the FSCD IE shall be used to indicate that the TID field is not present in the fragments during that transaction. When the FSCD IE is received with the Secure Fragment field set to one, the PSDU Counter field shall be used with the fragment number to form the Frame Counter field used to construct the nonce, as described in 9.3.2.3.

23.3.3 Fragmentation

The MPDU is prepared for fragment transmission according to the following steps:

- 1) Divide the remaining MPDU into fragments of the size supported by the current PHY configuration. All fragments, with the exception of the final fragment, shall contain the maximum number of data octets. For PHY configurations that use a fixed PPDU size (i.e., no PPDU length field transmitted), the final fragment data shall be padded with *phyPsduFragPadValue*; the FICS field for the final fragment shall be calculated including the pad octets. When a PHY configuration only supports a fixed size PSDU, the size of each fragment shall be the PSDU size configured for that PHY; for all other PHYs, the fragment size shall be equal to the value of *phyPsduFragSize*.
- 2) Determine the TID.
- 3) If Secure Fragment is set to one, set the PSDU Counter value to the *phyPsduFragFrameCounter*. If the PSDU Counter has value of 0x3ff ffff then return error, otherwise increment the *phyPsduFragFrameCounter*.
- 4) Determine the FSCD IE.
- 5) Construct the Data frame containing the FSCD IE and then transmit it.
- 6) Upon acknowledgment of the fragment context frame, transmit the fragments. Wait for the Frak frames according to the Frak policy value, described in 23.3.7.2, which is specified in the FCSD IE. Retransmit the Fragment frame preceding the Frak if the acknowledgment is not received within the Frak timeout period.
- 7) Upon reception of the final fragment and/or transmission of the final Frak as appropriate, the reassembled PSDU is processed as described in 23.3.8.

Fragments shall be transmitted beginning with fragment 1 and ending with fragment *n*. The Frak is described in 23.3.7.3. The receiving device may terminate a transaction by sending a Frak to the transmitter with the Fragment Number field set to zero and the Frak Content set to zero.

23.3.4 Fragment packet

The Fragment packet shall be formatted as illustrated in Figure 23-10.

Octets: 2	variable	2/4
Fragment Header	Fragment Data	FICS

Figure 23-10—Fragment packet format

The Fragment Header field shall be formatted as illustrated in Figure 23-11.

Bits: 0–2	3–9	10–15
Frame Type	TID	Fragment Number

Figure 23-11—Fragment Header field format

The Frame Type field shall be set to indicate a Fragment frame, as defined in 7.2.2.2.

The TID field shall contain the value assigned to the transaction context, as indicated in the FSCD IE. Upon reception, if the TID field contains a value other than the TID of a currently active transaction, the Fragment packet is ignored (i.e., not acknowledged and not counted to reset the transaction timeout).

The Fragment Number field identifies the fragment contained in the Fragment Data field. Upon PSDU reassembly, the fragmented data shall be placed in order according to fragment number. A Fragment Number field value of 0x3f is reserved for future use. The first fragment sent shall have the Fragment Number field set to one.

The Fragment Data field contains the part of the fragmented PSDU indicated by the Fragment Number field. The size of the data field depends on the configuration of the PHY in use.

The FICS field is used to validate the received fragment. When *phyPsduFragSecure* is FALSE, the length of the field shall be that indicated by the FICS Length field in the FSCD IE, and it shall be calculated according to 7.2.11. When *phyPsduFragSecure* is TRUE, the length of the field shall be 4 octets and shall contain the MIC-32, as described in 23.3.5.

Devices that support fragmentation shall support the reception of either the 2-octet or 4-octet FICS.

23.3.5 Calculating FICS field using MIC

When the FSCD IE Secure Fragment field for the transaction is set to one, the length of the FICS field shall be 4 octets and shall contain the MIC-32 calculated as described in this subclause.

The nonce for the CCM transformation is calculated as specified in the 9.3.2.3. The Private Payload field is set to empty, The Open Payload field is set to contain the Fragment Header and Fragment Data. The SecurityLevel is set to one.

The key is set to be the same key that was used to protect the frame containing the FSCD IE negotiating the exchange, i.e., secure fragments can only be used if security was enabled when setting the transaction up.

The CCM transformation shall then use the Private Payload field, the Open Payload field, the macExtendedAddress, the SecurityLevel, and the key to produce the secured fragment according to the AEAD transformation process defined in 9.3.4.

23.3.6 Fragment acknowledgment and retransmission

Two levels of acknowledgment are provided: acknowledgment of fragments during the transfer process (i.e., Frak), which provide *progress reports*; and acknowledgment of the reassembled MPDU, as described in 6.6.3.3.

To accommodate individual fragment acknowledgments, a FICS is included with each fragment. The recipient device uses the FICS and fragment number to determine the fragments of the sequence have been received correctly and the ones that are missing.

The Frak reports the fragments that have been successfully received up to that point. It is generated incrementally during the fragment sequence transfer according to the Frak policy provided in the FSCD IE.

23.3.7 Frak

23.3.7.1 General

The Frak frame is used during the fragment sequence transfer to determine which fragments have been received successfully and which fragments need to be retransmitted. A Frak frame includes the status of one or more fragments. The format of the Frak frame is given in 23.3.7.3.

The interval of the Frak frame is determined by the Frak Policy field, defined in 23.3.7.2. Upon completing the transmission of the fragment preceding the expected Frak frame according to the Frak policy selected, the initiating device shall suspend transmission and wait for the expected Frak frame. Upon reception of the Frak, fragments indicated as not received correctly shall be retransmitted. The number of retransmissions shall be limited by *macMaxFrameRetries* per fragment.

Upon reception of a fragment, the FICS is validated. The receiving device shall generate a Frak frame according to the Frak policy in use. The Frak frame shall be transmitted at the next transmit opportunity following the triggering condition.

When Frak policy zero is in use, reception of an out-of-order fragment shall result in termination of the transaction.

Frak frames are not secured.

23.3.7.2 Frak policy

The Frak Policy field shall be set to one of the non-reserved values given in Table 23-4.

Table 23-4—Frak Policy field values

Field value	Frak policy description
0	A Frak frame shall be sent upon reception of each fragment.
1	Acknowledgment based on time: A Frak frame shall be generated if <i>phyPsduFrakProgressTimeout</i> has elapsed since the reception of the fragment context frame or the last received fragment, whichever is later. In this mode, the originator will never stop waiting to get a Frak, even if the target does not want to Frak.
2	Acknowledge the last outstanding fragment: A Frak frame shall be generated only when the last expected fragment is received, or if <i>phyPsduFrakProgressTimeout</i> has elapsed since the last received fragment.
3	Reserved

23.3.7.3 Frak format

The Frak shall be formatted as illustrated in Figure 23-12.

Octets: 2	variable	2/4
Frak Header	Fragment Status	Frak Validation

Figure 23-12—Frak format

The Frak Header field shall be formatted as illustrated in Figure 23-13.

Bits: 0–2	3–9	10–15
Frame Type	TID	Fragment Number

Figure 23-13—Frak Header field format

The Frame Type field is defined in 23.3.4.

The TID field shall contain the same value as the TID in the received fragments being acknowledged.

The Fragment Number field is set to the value of the last fragment received prior to Frak generation.

The Fragment Status field shall be formatted as illustrated in Figure 23-14.

Bits: 0–3	4–7	8–23/8–39/8–55/8–71
Frak Content	LQI	Fragments Received (Set 0–Set 3)

Figure 23-14—Fragment Status field format

The Frak Content field shall be set to one of the values shown in Table 23-5 based on the number of Fragment Received bits that are included in the Fragment Status field. Setting all bit positions to zero indicates an aborted transaction.

Table 23-5—Frak Content field

Bit position	Description
b0	Set to one if Fragment Received bits 0–15 are present, set to zero otherwise.
b1	Set to one if Fragment Received bits 16–31 are present, set to zero otherwise.
b2	Set to one if Fragment Received bits 32–47 are present, set to zero otherwise.
b3	Set to one if Fragment Received bits 48–63 are present, set to zero otherwise.

The LQI field is an unsigned integer that is an indication of the signal quality of the received fragment(s) being acknowledged. The measurement method is implementation dependent, and at least eight unique values of LQI should be provided. A larger value of the LQI field is used to indicate a higher quality signal.

The Fragments Received field indicates the status of received fragments up to the current point in the transaction. The status bits are grouped into 4 bitmaps of 16 bits each. The status for fragment number n is contained bit n of the Fragments Received field. When more than one set is included in the Frak, the lowest numbered set is transmitted first in time, so that the corresponding fragment numbers go from low to high as transmitted.

Once all fragments from a group have been acknowledged, the corresponding group may be omitted from subsequent Frak frames of the same transaction.

The Frak Validation field is used to validate the received Frak. The length of the field shall be determined by the FICS Length field contained in the FSCD IE, and it shall be calculated according to 7.2.11, except that the initial remainder value used for CRC calculation shall be as described in 10.15.2.1.

23.3.8 Reassembly

Upon reception of the frame containing the FSCD IE, the frame containing the FSCD IE is acknowledged and the transaction state is initialized for a new PSDU fragment sequence transaction. Each received fragment is placed into the reassembled PSDU based on the value of the corresponding Fragment Number field. Fraks are generated according to 23.3.6. When the final fragment is received and validated, the FCS is presumed successful (without requiring an FCS of the frame) and processing proceeds according to 6.6.3.3. The receiving device is not required to validate the FCS of the PSDU nor is it required to send an Imm-Ack frame or Enh-Ack frame.

23.4 DSSS PHY RF requirements

23.4.1 Radio frequency tolerance

The DSSS PHY radio frequency tolerance shall be $\pm 2.5 \times 10^{-6}$.

23.4.2 Channel switch time

Channel switch time shall be less than or equal to 500 μ s. The channel switch time is defined as the time elapsed at the antenna between the trailing edge of the last symbol of one PPDU to the leading edge of the first symbol of a consecutive PPDU sent on a different channel.

23.4.3 Transmit spectral mask

Implementers are responsible to assure that the transmit spectral content conforms to all local regulations.

23.4.4 Receiver sensitivity

The receiver sensitivity information is given in Table 23-6. The PER is $\leq 1\%$ for the following conditions: BPSK modulation, no tail biting, fragment length of 16 octets, a 2-octet preamble and an 8-bit SFD.

Table 23-6—Minimum LECIM DSSS PHY receiver sensitivity (dBm)

Spreading factor (chips/bit)	Modulation rate (ksym/s)				
	200	400	600	800	1000
16	-115	-112	-110	-109	-108
32	-118	-115	-113	-112	-111
64	-121	-118	-116	-115	-114
128	-124	-121	-119	-118	-117
256	-127	-124	-122	-121	-120
512	-130	-127	-125	-124	-123
1024	-133	-130	-128	-127	-126
2048	-136	-133	-131	-130	-129
4096	-139	-136	-134	-133	-132
8192	-142	-139	-137	-136	-135
16384	-145	-142	-140	-139	-138
32768	-148	-145	-143	-142	-141

23.4.5 Receiver interference rejection

The minimum receiver interference rejection levels are given in Table 23-7. The adjacent channels are those on either side of the desired channel that are closest in frequency to the desired channel. The alternate channel is more than one removed from the desired channel in the operational frequency band.

Table 23-7—LECIM DSSS minimum receiver interference rejection requirements

Adjacent channel rejection	Alternate channel rejection
10 dB	30 dB

The adjacent channels are as follows:

$$\text{ChanNum} \pm (1 \times \text{phyLecimDsssP pdu Modulation Rate} / \text{Spacing})$$

The variable *ChanNum* is the channel identifier number of the designated channel, *phyLecimDsssP pdu Modulation Rate* is defined in 12.3, and *Spacing* is *ChanSpacing* \times 1000 (*ChanSpacing* is defined in 11.1.3.11.2). The alternate channels are as follows:

$$\text{ChanNum} \pm (2 \times \text{phyLecimDsssP pdu Modulation Rate} / \text{Spacing})$$

23.4.6 TX-to-RX turnaround time

The DSSS PHY shall meet the requirements for TX-to-RX turnaround time, as defined in 11.2.2.

23.4.7 RX-to-TX turnaround time

The DSSS PHY shall meet the requirements for RX-to-TX turnaround time, as defined in 11.2.3.

23.4.8 Transmit power

A transmitter shall be capable of transmitting at least -3 dBm. The maximum transmit power is limited by local regulatory bodies.

24. LECIM FSK PHY specification

24.1 Introduction

The LECIM FSK PHY is specified for use in applications requiring very low power consumption and long-range communications. Besides the classical packet transmission it offers an additional split mode for improved robustness in highly congested license-exempt frequency bands.

24.2 General

LECIM FSK transmission supports two different modes: split and non-split. When *phyLecimFskSplit* is set to true, split mode shall be enabled, when it is set to false, non-split mode shall be enabled. The mode is preconfigured and switching between the modes during operation is not supported.

In non-split mode, a PSDU is transmitted in a single packet. In split mode, the PSDU and PHR are jointly FEC encoded and split to form multiple radio-burst payloads that are transmitted on different channels at different times.

The difference between split and non-split mode is illustrated in Figure 24-1.

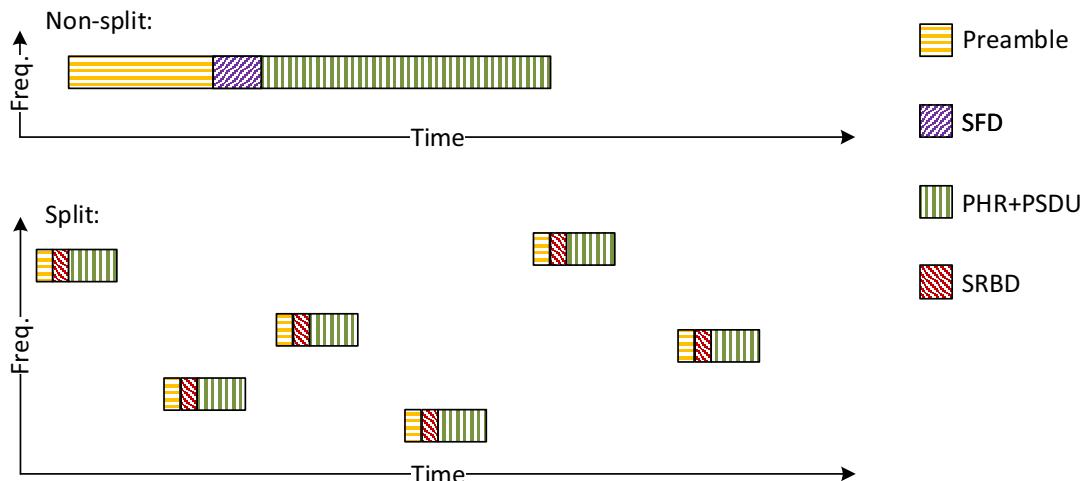


Figure 24-1—Comparison of non-split mode vs split mode

A single radio-burst is not decodable on its own; instead, multiple radio-bursts have to be combined to reconstruct the PSDU. The minimum number of collected radio-bursts for successful reconstruction is dependent on the applied FEC.

A device may support non-split or split mode or both.

The intention of the LECIM FSK Operating Mode IE is to allow a higher layer to perform remote configuration of a LECIM FSK device in an interoperable manner.

24.3 PPDU format for LECIM FSK PHY

24.3.1 General

The LECIM FSK PPDU shall support the format shown in Figure 24-2.

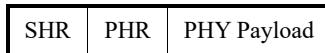


Figure 24-2—Format of the LECIM FSK PPDU

24.3.2 SHR field format

24.3.2.1 General

The SHR field shall be formatted as illustrated in Figure 24-3.

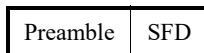


Figure 24-3—Format of the SHR

24.3.2.2 Preamble field format

The attribute *phyLecimFskPreambleLength*, as described in 12.3.5, controls the length of the preamble. The Preamble field shall contain *phyLecimFskPreambleLength* multiples of the 8-bit sequence “01010101”. The preamble field shall be omitted when *phyLecimFskPreambleLength* equals zero.

In non-split mode, for the purposes of calculating the Ack frame timing required in 6.6.4, the Preamble field length of four octets shall be used.

For split mode, the Ack frame timing shall be calculated based on the first radio-burst and using the Preamble field length of zero octets.

24.3.2.3 SFD field format

The SFD is only used in non-split mode. The SFD shall be a 3-octet sequence, as shown in Figure 24-4.

The SFD is transmitted starting from the leftmost bit.

Octets	1	2	3
Bit map	0111 0000	1110 1110	1101 0010

Figure 24-4—SFD value for LECIM FSK PHY

24.3.3 PHR field format

The format of the PHR is shown in Figure 24-5.

Bits: 0–1	2	3	4	5–15
Reserved	Parity	FCS Type	Data Whitening	Frame Length

Figure 24-5—PHR field format

The Parity field is calculated in the following way:

$$\text{Parity field} = b_3 \oplus b_4 \oplus b_5 \oplus b_6 \oplus b_7 \oplus b_8 \oplus b_9 \oplus b_{10} \oplus b_{11} \oplus b_{12} \oplus b_{13} \oplus b_{14} \oplus b_{15}$$

The FCS Type field specifies the length of the FCS field, as defined in 7.2.11. A value of zero indicates a 4-octet FCS field, and a value of one indicates a 2-octet FCS field.

The Data Whitening field shall be set to one if data whitening is used in the packet and shall be set to zero otherwise.

The Frame Length field is an unsigned integer that shall be set to the total number of octets contained in the PSDU (prior to FEC encoding, if enabled). The MSB shall be transmitted first.

For non-split mode, the full 11-bit range PSDU size given by the Frame Length field shall be supported.

The maximum PSDU size for split mode shall be 184 octets.

NOTE—The actual PSDU size may not be known to the receiver before reception of the last radio burst. A lower maximum PSDU size may be chosen based on implementation requirements.

24.3.4 PHY Payload field

The PHY Payload field carries the encoded PSDU.

24.3.5 Radio-burst format for split mode

The structure of radio-burst is depicted in Figure 24-6.

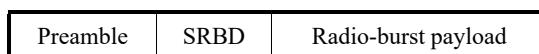


Figure 24-6—Radio-burst structure

The preamble shall be formed as described in 24.3.2.2. The start of radio-burst delimiter (SRBD) shall be formed as depicted in Figure 24-7.

Bits: 0–3	4–15
1010	1101 1110 1000

Figure 24-7—SRBD value

A receiver shall always assume a maximum length radio-burst payload that depends on the utilized FEC and the actual payload sizes in the deployed network.

24.4 Modulation and coding for LECIM FSK PHY

24.4.1 General

The modulation for the non-split LECIM FSK PHY shall be FSK or position-based FSK (P-FSK). The modulation index for each modulation and bit rate is given in Table 24-1.

Table 24-1—Non-split LECIM FSK PHY modulation

Band	Modulation index	Modulation	Bit rate (kb/s)
169 MHz	0.5	FSK/P-FSK	25
	1.0		12.5
262 MHz	2.0	FSK/P-FSK	2.4
	1.0		4.8
All other bands	0.5	FSK/P-FSK	37.5
	1.0		25
	2.0		12.5
	2.0		6.25

Channel spacing may be used as permitted by local regulations. Available channel spacings are given in 11.1.3.11.3.

For split mode, the modulation shall be as follows:

Modulation index shall be 0.5 for all symbol rates. The modulation shall be shaped FSK that complies with the required modulation quality as given in 24.4.4.

The symbol rate shall be one of the following symbol rates: *lecimBaseMultiplier* ksymbols/s, $2 \times \text{lecimBaseMultiplier}$ ksymbols/s, $4 \times \text{lecimBaseMultiplier}$ ksymbols/s, or $8 \times \text{lecimBaseMultiplier}$ ksymbols/s.

NOTE—These symbol rates and channel spacings are directly derived from the common oscillator frequency of current transceivers and are required due to the narrowband nature of the signal.

A device supporting split mode shall support the symbol rate *lecimBaseMultiplier* kSymbols/s with a channel spacing of *lecimBaseMultiplier* kHz and may additionally support the other modes.

The symbol timing used for the MAC and PHY timing parameters shall be as follows:

$$\frac{1}{\text{phyLecimFskSymbolRate}} \text{ ms}$$

The use of P-FSK modulation for PSDU data is controlled by the PIB attribute *phyLecimFskPsduPositionMod*, as defined in 12.3.5. The modulation for preamble, SFD, and PHR shall be FSK regardless of the value of *phyLecimFskPsduPositionMod*.

FSK encodes one bit by transmitting a frequency modulated signal $m(t)$ with duration T_s , i.e., $0 \leq t < T_s$. P-FSK encodes two bits by transmitting a FSK modulated signal $m(t)$ with T_s duration in one of two possible positions (also known as time deviation), i.e., $0 \leq t < T_S$ and $T_S \leq t < 2T_S$.

24.4.2 Reference modulator

24.4.2.1 Reference modulator for split mode

The functional block diagram of the reference modulator for split mode is illustrated in Figure 24-8.

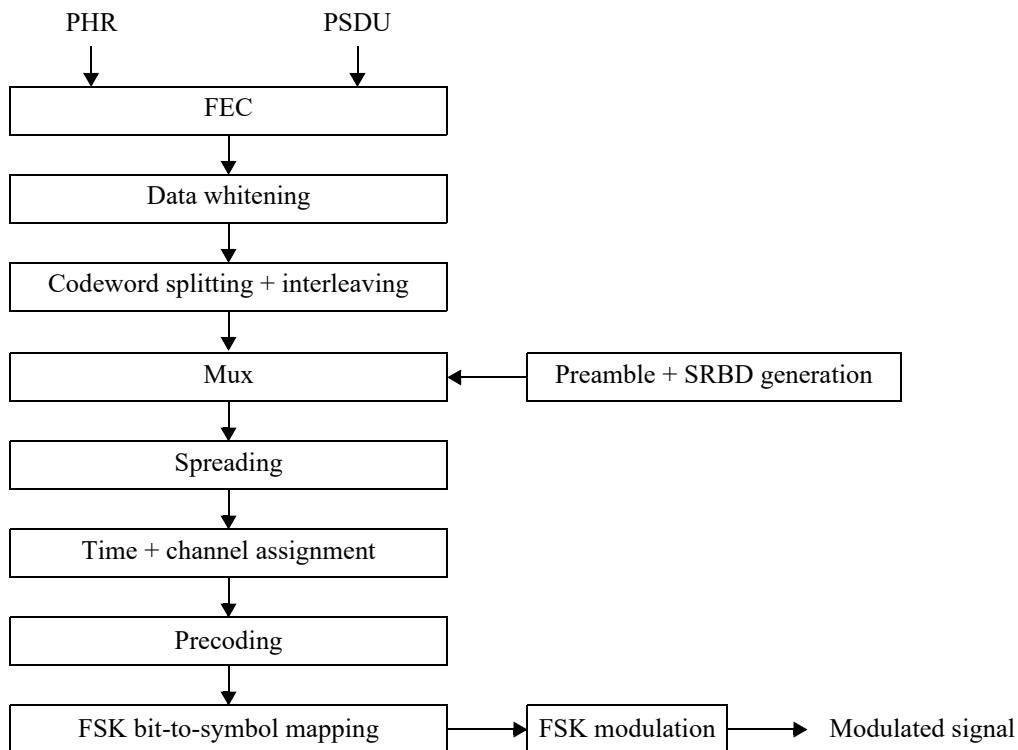


Figure 24-8—Split mode LECIM FSK reference modulator diagram

When FEC is enabled, the PHR and PSDU shall be processed for coding, as described in 24.4.5.3. Data whitening is done as described in 24.5.

Codeword splitting and interleaving as described in 24.4.7, shall be applied to generate the radio-burst payloads.

Each radio-burst payload shall be multiplexed with the preamble and the SRBD to form the radio-burst as described in 24.3.5.

Spreading may be used. When it is enabled, it shall be applied over the SRBD and the radio-burst payload, as described in 24.4.10.

The resulting radio-burst shall be assigned a time and channel for transmission. Precoding shall be done over all fields of the radio-burst, as described in 24.4.9, for each radio-burst individually.

The FSK bit-to-symbol mapping and FSK modulation shall be applied as described in 24.4.3, after which the radio-burst shall be transmitted at its assigned time and channel.

24.4.2.2 Reference modulator for non-split mode

The functional block diagram of the reference modulator for non-split mode is illustrated in Figure 24-9.

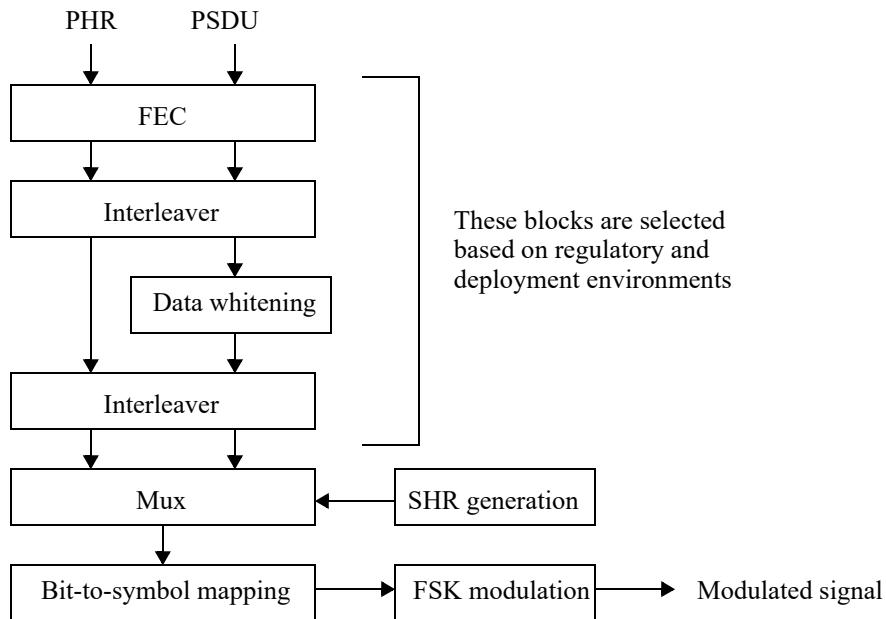


Figure 24-9—Non-split mode LECIM FSK reference modulator diagram

When FEC is enabled, the PHR and PSDU shall be processed for coding, as described in 24.4.5.2. When data whitening is enabled, the scrambling shall be only applied over the PSDU, as described in 24.5.

When spreading is enabled and SFD spreading is disabled, according to *phyLecimFskSfdSpreading*, the spreading shall be applied over the PHR and PSDU. When spreading is enabled and SFD spreading is enabled, the spreading shall be applied over the SFD the PHR and the PSDU. Spreading shall be applied as described in 24.4.10.

All fields in the PPDU shall use the same symbol rate and modulation order, unless otherwise specified elsewhere in this standard.

The FSK bit-to-symbol mapping and FSK modulation shall be applied as described in 24.4.3, after which the radio-burst shall be transmitted at its assigned time and channel.

24.4.3 Bit-to-symbol mapping

The nominal frequency deviation, f_{dev} , shall be $(\text{symbol rate} \times \text{modulation index})/2$.

The symbol encoding for FSK and P-FSK modulation is shown in Table 24-2 and Table 24-3, respectively.

Table 24-2—FSK symbol encoding

Symbol (b0)	Frequency deviation	Time deviation
0	$-f_{\text{dev}}$	0
1	$+f_{\text{dev}}$	0

Table 24-3—P-FSK symbol encoding

Symbol (b0, b1)	Frequency deviation	Time deviation
00	$-f_{\text{dev}}$	0
01	$-f_{\text{dev}}$	T_s
10	$+f_{\text{dev}}$	0
11	$+f_{\text{dev}}$	T_s

24.4.4 Modulation quality

24.4.4.1 General

Modulation quality shall be measured by observing the frequency deviation tolerance and the zero crossing tolerance of the eye diagram caused by a PN9 sequence of length 511 bits.

24.4.4.2 Frequency deviation tolerance

For non-split mode, the frequency deviation tolerance shall be as given in 20.3.4.2 for 2-level modulation.

In split mode, modulation frequency tolerance is measured as a percentage of the frequency deviation f_{dev} . The measured frequency deviation at position $|T_{s(\text{recovered})}| = 0.5$ (position 1 in Figure 24-10) shall not exceed $90\% f_{\text{dev}} \leq |f| \leq 110\% f_{\text{dev}}$.

In split mode, in case of a bit transition, the frequency deviation of $|f| = 50\% f_{\text{dev}}$ shall be measured at position $|T_{s(\text{recovered})}| = 0.09$ within ± 0.04 of the symbol time T_s (position 2 in Figure 24-10).

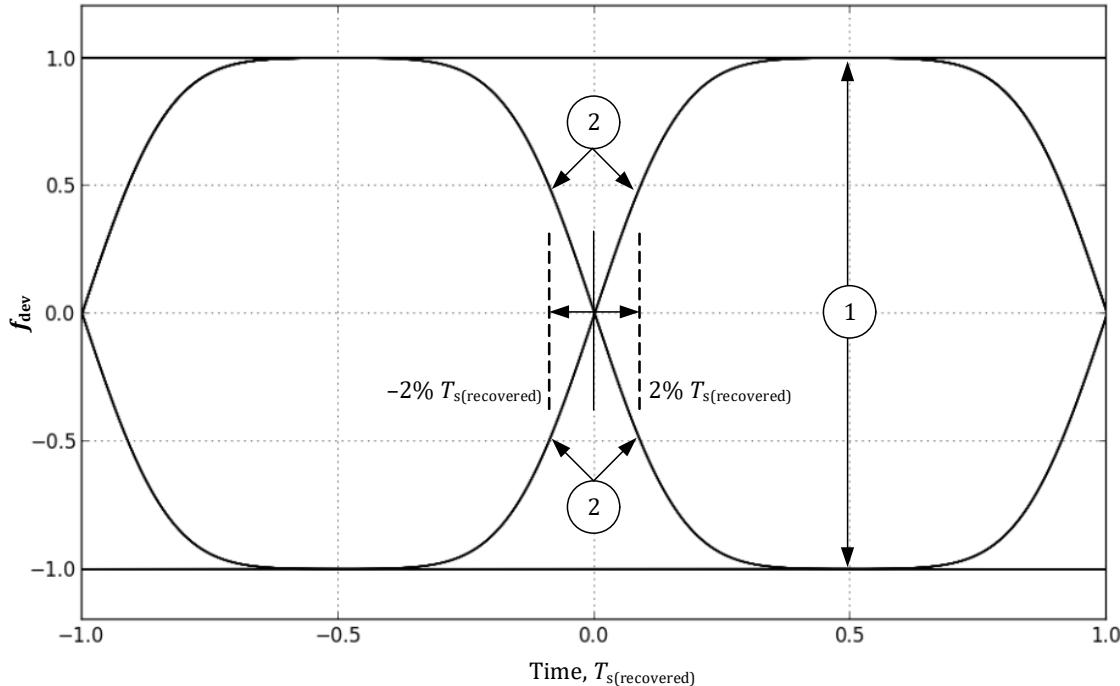


Figure 24-10—Eye diagram of split mode FSK

NOTE—The eye diagram shown in Figure 24-10 corresponds to what is commonly referred to as GFSK with a BT of 1.0.

The symbol timing accuracy shall be better than $\pm 20 \times 10^{-6}$.

24.4.4.3 Zero crossing tolerance

In non-split mode, the excursions for the zero crossings for all trajectories of the eye diagram shall be constrained as specified in 20.3.4.3.

In split mode, the excursion for the zero crossings for all trajectories in the eye diagram shall be constrained within $\pm 2\%$ RMS of the symbol time T_s , as shown in Figure 24-10.

24.4.5 FEC

24.4.5.1 General

In non-split mode, the use of FEC is controlled by the PIB attribute *phyLecimFskFecEnabled*, as defined in 12.3.5. The FEC is described in 24.4.5.2. In split mode, FEC shall be used as described in 24.4.5.3.

24.4.5.2 Non-split FEC

When used, FEC shall employ rate 1/2 convolutional coding with constraint length $K = 7$, as shown in Figure 24-11, where \oplus denotes modulo-2 addition.

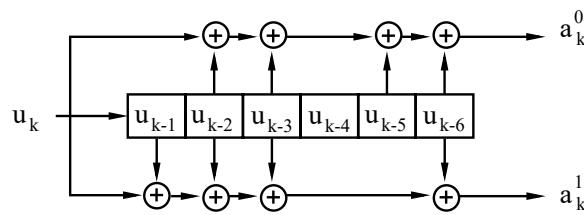


Figure 24-11—LECIM FSK PHY convolutional encoder

Prior to the convolutional encoding of the PHR bits, as described in 24.3.3, the initial encoder state at $k = 0$ shall be set as follows:

$$(u_{-1}, u_{-2}, \dots, u_{-6}) = (0, 0, 0, 0, 0, 0)$$

and the sequence of PHR bits shall be extended by a termination sequence of six bits, all zero, as shown in Figure 24-12.

Prior to the convolutional encoding of the PSDU, the sequence of PSDU bits $b = \{b_0, b_1, \dots, b_{8 \times \text{LENGTH}-1}\}$, with its length (LENGTH) measured in octets, shall be extended by appending a termination sequence of six bits, all zero, and a sequence of additional bits (pad bits) as shown in Figure 24-12.

PHR bits	Termination sequence	PSDU bits	Termination sequence	pad bits
----------	----------------------	-----------	----------------------	----------

Figure 24-12—PHR and PSDU extension prior to encoding

The pad bits shall be set to zero; and the number of pad bits, N_{PAD} , is computed from the number of blocks, N_B ; the total number of uncoded bits, N_D ; and the interleaver depth, N_{DEPTH} , as follows:

$$N_B = \text{ceiling}((8 \times \text{LENGTH} + 6)/(N_{\text{DEPTH}}/2))$$

$$N_D = N_B \times (N_{\text{DEPTH}}/2)$$

$$N_{\text{PAD}} = N_D - (8 \times \text{LENGTH} + 6)$$

where the value of $N_{\text{DEPTH}} = N_{\text{PSDU}}$ is given in Table 24-5. The function ceiling() is a function that returns the smallest integer value greater than or equal to its argument value.

The sequence shown in Figure 24-12 shall be passed to the convolutional encoder. The corresponding output sequence of code bits, z , shall be generated as follows:

$$z = \{\dots a_k^0, a_k^1, a_{k+1}^0, a_{k+1}^1, a_{k+2}^0, a_{k+2}^1 \dots\} = \{z_0, z_1, \dots, z_{[2N_D + (N_{\text{DEPTH}} - 1)]}\}$$

i.e., a_k^0 is preceding sample a_k^1 . The first sample, z_0 , shall be passed to the interleaver first in time, and the last sample, $z_{[2N_D + (N_{\text{DEPTH}} - 1)]}$, shall be passed to the interleaver last in time. The value of $N_{\text{DEPTH}} = N_{\text{PHR}}$ is defined in Table 24-5.

24.4.5.3 Split FEC

24.4.5.3.1 General

The PHR and PSDU shall always be FEC coded. The applied FEC shall be chosen depending on the PIB attribute *phyLecimFskSplitFec*. The three available FEC modes, rate 1/2 convolutional code, rate 1/3 convolutional code, and rate 1/4 low density parity check (LDPC) code are described in the following subclauses.

A device shall support the rate 1/3 convolutional code and may additionally support the other modes.

24.4.5.3.2 Rate 1/2 convolutional code

When *phyLecimFskSplitFec* is set to 1R2-CC, the FEC shall employ a rate 1/2 convolutional coding with constraint length $K = 7$. The PHR bits and PSDU bits shall be concatenated and extended by a sequence of six zeros as shown in Figure 24-13 before being used as the input sequence for the encoder.

PHR	PSDU	000000
-----	------	--------

Figure 24-13—Input sequence of the split convolutional encoder

The encoder is shown in Figure 24-11, where \oplus denotes modulo-2 addition.

The initial encoder state at $k = 0$ shall be all zero. The corresponding output sequence of code-bits, z , shall be generated as follows:

$$z = \{a_k^0, a_k^1, a_{k+1}^0, a_{k+1}^1, a_{k+2}^0, a_{k+2}^1, \dots\} = \{z_0, z_1, z_2, \dots, z_{N_{\text{FEC}} - 1}\}$$

where N_{FEC} denotes the length of the bit sequence after the FEC encoding.

24.4.5.3.3 Rate 1/3 convolutional code

When *phyLecimFskSplitFec* is set to 1R3-CC, the FEC shall employ a rate 1/3 convolutional coding with constraint length $K = 7$. The PHR bits and PSDU bits shall be concatenated and extended by a sequence of six zeros as shown in Figure 24-13 before being used as input for the encoder.

The encoder is shown in Figure 24-14, where \oplus denotes modulo-2 addition.

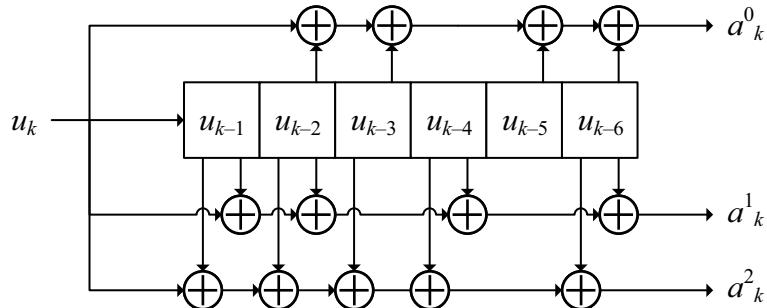


Figure 24-14—Rate 1/3 convolutional encoder

The initial encoder state at $k = 0$ shall be all zero. The corresponding output sequence of code-bits, z , shall be generated as follows:

$$z = \{a_k^0, a_k^1, a_k^2, a_{k+1}^0, a_{k+1}^1, a_{k+1}^2, a_{k+2}^0, a_{k+2}^1, a_{k+2}^2, \dots\} = \{z_0, z_1, z_2, \dots, z_{N_{\text{FEC}}-1}\}$$

where N_{FEC} denotes the length of the bit sequence after the FEC encoding.

24.4.5.3.4 Rate 1/4 LDPC code

When *phyLecimFskSplitFec* is set to 1R4-LDPC, the FEC shall employ a rate 1/4 LDPC code. PHR bits and PSDU bits are concatenated and extended by a sequence of pad bits, as shown in Figure 24-15, to form the input of the LDPC encoder.



Figure 24-15—Input sequence of the rate 1/4 LDPC encoder

The pad bits shall be set to zero, and guarantee that the total number of input bits for the LDPC encoder is a multiple of 184 bits. This sequence is then split into information sequences of length $K_{\text{LDPC}} = 184$ bits (23 octets).

A systematic binary LDPC code of rate 1/4 appends $M_{\text{LDPC}} = 552$ parity bits to each information sequence. The LDPC has quasi-cyclic structure (information part) and dual staircase (parity part), that is parities shall be accumulated (see below). Encoding shall be done as follows:

- The first K_{LDPC} code-bits shall be equal to the information bits ($z_k = i_k$), the value of the remaining M_{LDPC} parity bits $p_0, p_1, p_2, \dots, p_{M_{\text{LDPC}}-1}$ is described below.
- The initial value of all parity bits shall be $p_0 = p_1 = p_2 = \dots = p_{M_{\text{LDPC}}-1} = 0$.

- The first information bit, i_0 , shall be accumulated with parity bits at addresses specified in the first row of Table 24-4.

For example (all additions are in Galois Field 2):

$$\begin{array}{ll} p_1 = p_1 \oplus i_0 & p_7 = p_7 \oplus i_0 \\ p_{90} = p_{90} \oplus i_0 & p_{172} = p_{172} \oplus i_0 \\ p_{209} = p_{209} \oplus i_0 & p_{359} = p_{359} \oplus i_0 \\ p_{401} = p_{401} \oplus i_0 & p_{420} = p_{420} \oplus i_0 \\ p_{483} = p_{483} \oplus i_0 & p_{487} = p_{487} \oplus i_0 \end{array}$$

- The next 7 information bits, i_m , with $m = 1, 2, \dots, 7$, shall be accumulated with parity bits at addresses $(x + (m \bmod 8) \times Q_{\text{LDPC}}) \bmod M_{\text{LDPC}}$, where x denotes the address of the parity bit accumulator corresponding to the first bit i_0 , and $Q_{\text{LDPC}} = 69$.

For example, for information bit i_1 , the following operations are performed:

$$\begin{array}{ll} p_{70} = p_{70} \oplus i_1 & p_{76} = p_{76} \oplus i_1 \\ p_{159} = p_{159} \oplus i_1 & p_{241} = p_{241} \oplus i_1 \\ p_{278} = p_{278} \oplus i_1 & p_{428} = p_{428} \oplus i_1 \\ p_{470} = p_{470} \oplus i_1 & p_{489} = p_{489} \oplus i_1 \\ p_0 = p_0 \oplus i_1 & p_4 = p_4 \oplus i_1 \end{array}$$

For the 9th information bit i_8 , the addresses of the parity bit accumulators are given in the second row of Table 24-4. In a similar manner, the addresses of the parity bit accumulators for the following 7 information bits i_m , with $m = 9, 10, \dots, 15$, shall be obtained using the formula $(x + (m \bmod 8) \times Q_{\text{LDPC}}) \bmod M_{\text{LDPC}}$, where x denotes the address of the parity bit accumulator corresponding to the information bit i_8 , that is the entries in the second row of Table 24-4.

- In a similar manner, for every group of 8 new information bits, a new row from the Table 24-4 shall be used to find the addresses of the parity bit accumulators.

Table 24-4—Addresses of the LDPC parity bits

1	7	90	172	209	359	401	420	483	487
57	164	192	197	284	307	174	356	408	425
22	50	191	379	385	396	427	445	480	543
32	49	71	234	255	286	297	312	537	550
30	70	88	111	176	201	283	322	419	499
86	94	177	193	266	368	373	389	475	529
134	223	242	254	285	319	403	496	503	534
18	84	106	165	170	199	321	355	386	410
129	158	226	269	288	316	397	413	444	549
33	113	133	194	256	305	318	380	507	
317	354	402							
53	64	374							
83	314	378							
162	259	280							
166	281	486							

Table 24-4—Addresses of the LDPC parity bits (*continued*)

185	439	489						
119	156	224						
26	62	244						
8	246	482						
15	72	91						
43	69	390						
127	186	506						
55	81	412						

After all of the information bits are exhausted, the final parity bits shall be obtained by accumulation as follows:

- Sequentially the operations starting with $i = 1$ shall be performed as follows:
 $p_i = p_i \oplus p_{i-1}$ for $i = 1, 2, \dots, M_{\text{LDPC}} - 1$
- Final content of $p_i = 1, 2, \dots, M_{\text{LDPC}} - 1$ shall be equal to the parity bit p_i .

The corresponding output sequence of code-bits, z , shall be generated as follows:

$$z = \{i_0, i_1, i_2, \dots, i_{K_{\text{LDPC}} - 1}, p_0, p_1, p_2, \dots, p_{M_{\text{LDPC}} - 1}\} = \{z_0, z_1, z_2, \dots, z_{N_{\text{FEC}} - 1}\}$$

where $N_{\text{FEC}} = K_{\text{LDPC}} + M_{\text{LDPC}}$ denotes the length of the LDPC codeword after the FEC encoding.

24.4.6 Code-bit interleaving for non-split mode

The use of interleaving is controlled by the PIB attribute *phyLecimFskInterleavingEnabled*, as defined in 12.3.5.

Since the PHR bits are terminated, PHR code bits and PSDU code bits are independent code blocks. Interleaving of PHR code bits is separate from the interleaving of the PSDU code bits.

Interleaving of code bits shall be employed in conjunction with FEC. No code-bit interleaving shall be employed if FEC is not used.

The sequence of PHR code bits consists of a single sequence:

$$z^0 = \{z_0^0, \dots, z_{N_{\text{PHR}} - 1}^0\}$$

of length N_{PHR} .

The sequence of PSDU code bits consists of N_B subsequences:

$$z^j = \{z_0^j, \dots, z_{N_{\text{PSDU}} - 1}^j\} = \{z_{(j-1)N_{\text{PSDU}} + N_{\text{PHR}}}^j, \dots, z_{jN_{\text{PSDU}} + N_{\text{PHR}} - 1}^j\} \text{ for } j = 1, \dots, N_B$$

of length N_{PSDU} .

The interleaver is defined by a permutation. The index of the code bits before the permutation shall be denoted by k , where $k = 0$ refers to the first sample, z_0^j , and $k = N_{\text{DEPTH}} - 1$ refers to the last sample, $z_{N_{\text{DEPTH}}-1}^j$, passed to the interleaver for a given subsequence z^j . The index i shall be the index after the permutation. The permutation is defined by the following rule:

$$i = \frac{N_{\text{DEPTH}}}{\lambda} \times ((N_{\text{DEPTH}} - 1 - k) \bmod \lambda) + \text{floor}\left(\frac{N_{\text{DEPTH}} - 1 - k}{\lambda}\right) \quad k = 0, \dots, N_{\text{DEPTH}} - 1$$

where the degree λ is given in Table 24-5. The function floor() is a function that returns the largest integer value less than or equal to its argument value.

Table 24-5—Parameters of the interleaver

Field	Degree λ	Depth N_{DEPTH}
PHR	4	$N_{\text{PHR}} = 4 \times 11 = 44$
PSDU	6	$N_{\text{PSDU}} = 6 \times 12 = 72$

The process of interleaving a subsequence is shown in Figure 22-12. The first subsequence, z^0 , shall be processed first in time and the last subsequence, z^{N_B} , shall be processed last in time.

The deinterleaver, which performs the inverse relation, is defined by the following rule:

$$k = \lambda \times (N_{\text{DEPTH}} - 1 - i) - (N_{\text{DEPTH}} - 1) \times \text{floor}\left(\frac{\lambda \times (N_{\text{DEPTH}} - 1 - i)}{N_{\text{DEPTH}}}\right) \quad i = 0, \dots, N_{\text{DEPTH}} - 1$$

24.4.7 Codeword splitting and interleaving for split mode

24.4.7.1 Supported methods

In split mode, the interleaver and splitting method change according to the utilized FEC and the resulting number of available radio-bursts, configured by *phyLecimFskSplitFec*, as shown in Table 24-6.

Table 24-6—Number of radio-bursts dependent on FEC mode

<i>phyLecimFskSplitFec</i>	Number of radio-bursts N_{RB}	Interleaver
1R2-CC	12	See 24.4.7.2
1R3-CC	18	See 24.4.7.2
1R4-LDPC	23	See 24.4.7.3

24.4.7.2 Convolutional interleaving

The sequence of FEC encoded bits z , given by:

$$z = \{z_0, z_1, z_2, \dots, z_{N_{\text{FEC}}-1}\}$$

shall be mapped over the N_{RB} radio-bursts, by a two dimensional $I \times N_{\text{RB}}$ scramble matrix M . I denotes the size of the radio-burst payload given by:

$$I = \left\lceil \frac{N_{\text{FEC}}}{N_{\text{RB}}} \right\rceil$$

The value of the matrix M at position (i, j) denotes the index n of the bit z_n which shall be placed in radio-burst payload j at position i , where $i = 0$ refers to the first bit after the SHR and $j = 0$ refers to the radio-burst payload of the first radio-burst to be transmitted.

The values of matrix M are given by:

$$M(i, j) = (i \times N_{\text{RB}}) + ((j - i + N_{\text{RB}}) \bmod N_{\text{RB}})$$

for:

$$i = \{0, 1, 2, \dots, I - 1\}$$

$$j = \{0, 1, 2, \dots, N_{\text{RB}} - 1\}$$

Values with $M(i, j) \geq N_{\text{FEC}}$ shall be ignored.

24.4.7.3 LDPC interleaving

The sequence z of 736 FEC encoded bits of a single codeword of the LDPC encoder shall be segmented into four equally sized chunks C_i :

$$z = \{C_0, C_1, C_2, C_3\} = \{z_0, z_1, z_2, \dots, z_{735}\}$$

$$C_i = \{z_{i \times 184}, z_{i \times 184 + 1}, z_{i \times 184 + 2}, \dots, z_{(i + 1) \times 184 - 1}\}$$

The second chunk C_1 shall be removed from the sequence. The remaining sequence y is given by:

$$y = \{C_0, C_2, C_3\} = \{y_0, y_1, y_2, \dots, y_{551}\}$$

The sequence y shall be pseudo-randomly scrambled using the scramble vector u , which is derived from the pseudo-random sequence v , generated by the 10-bit Galois LFSR as shown in Figure 24-16. The initial value of the LFSR at iteration 0 shall be $v_0 = 469$, with the feedback output of the LFSR representing the least significant bit. The LFSR in its initial state at iteration 0 is shown in Figure 24-16.

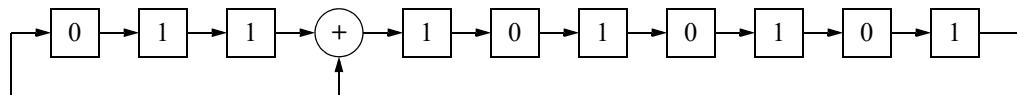


Figure 24-16—LFSR in its initial state

The value at iteration v_{i+1} is derived by iterating the shift register again. If the value of this iteration of the LFSR exceeds 552 the value is skipped and the LFSR is iterated again until the value does not exceed 552. This value is then assigned to v_{i+1} .

An informative example of the first values of v is given in Table 24-7.

Table 24-7—Example of scramble vector generation

LFSR iteration	LFSR value integer	LFSR value bit	Valid	Assigned to v
0	469	01 1101 0101	Yes	v_0
1	682	10 1010 1010	No	—
2	341	01 0101 0101	Yes	v_1
3	746	10 1110 1010	No	—
4	373	01 0111 0101	Yes	v_2
5

The vector u is given by $u_i = v_i - 1$ and the scrambled version of y , is given by:

$$y' = \{y_{u_0}, y_{u_1}, \dots, y_{u_{551}}\}$$

The second chunk C_1 shall be distributed over the N_{RB} radio-bursts by assigning every bit c_n of the chunk, a radio-burst index l and a position i within the radio-burst payload dependent on the index n as follows:

$$l(n) = \left\lfloor \frac{n}{2} \right\rfloor \bmod 23$$

$$i(n) = 2 \times \left\lfloor \frac{n}{46} \right\rfloor + (n \bmod 2)$$

with $n \in \{0, 1, 2, \dots, 183\}$, where $n = 0$ refers to the first bit c_0 of C_1 .

The bits of y' shall be assigned a radio-burst index l and a position i within the radio-burst payload dependent on the index m as follows:

$$l(m) = \left\lfloor \frac{m}{24} \right\rfloor$$

$$i(m) = 8 + (m \bmod 24)$$

with $m \in \{0, 1, 2, \dots, 551\}$, where $m = 0$ refers to the first bit y'_0 of y' .

In both cases $i = 0$ refers to the first bit of the radio-burst payload. If multiple codewords $\{cw_0, cw_1, \dots, cw_{N-1}\}$ are transmitted, $i = 0$ for the next codeword refers to the first bit after the already placed bits in the radio-burst payload, namely bit number $n \times 32 + 1$, where n denotes the number of the next codeword, since every LDPC codeword appends 32 bit to each radio-burst payload.

24.4.8 Radio-burst transmit time and channel selection

24.4.8.1 General

The attribute *phyLecimFskSplitBurstDistribution* controls the time and channel assignment method used for the radio-bursts. When *phyLecimFskSplitBurstDistribution* is set to FIXED, the radio-bursts shall be assigned a time and channel according to 24.4.8.2. When *phyLecimFskSplitBurstDistribution* is set to CUSTOM the assignment method shall be handled depending on regulatory and implementation needs.

24.4.8.2 Fixed distribution

When *phyLecimFskSplitBurstDistribution* is set to FIXED, time-channel patterns depend on the number of radio-bursts used for transmission. The time reference point of each radio-burst is the transmission start of its SRBD. The time interval between radio-burst $l - 1$ and radio-burst l is given in Table 24-8 in symbol durations for eight different patterns p .

Table 24-8—Time delay $T(p, l)$ depending on radio-burst number l and pattern p

$p \backslash l$		$T(p, l)$											
		1	2	3	4	5	6	7	8	9	10	11	12
0	330	387	388	330	387	354	330	387	356	330	387	432	
1	330	387	435	330	387	409	330	387	398	330	387	370	
2	330	387	356	330	387	439	330	387	413	330	387	352	
3	330	387	352	330	387	382	330	387	381	330	387	365	
4	330	387	380	330	387	634	330	387	360	330	387	393	
5	330	387	364	330	387	375	330	387	474	330	387	355	
6	330	387	472	330	387	546	330	387	501	330	387	356	
7	330	387	391	330	387	468	330	387	512	330	387	543	
$p \backslash l$		$T(p, l)$											
		13	14	15	16	17	18	19	20	21	22	23	
0	330	387	352	330	387	467	330	387	620	330	387		
1	330	387	361	330	387	472	330	387	522	330	387		
2	330	387	485	330	387	397	330	387	444	330	387		
3	330	387	595	330	387	604	330	387	352	330	387		
4	330	387	352	330	387	373	330	387	490	330	387		
5	330	387	478	330	387	464	330	387	513	330	387		
6	330	387	359	330	387	359	330	387	364	330	387		
7	330	387	354	330	387	391	330	387	368	330	387		

The relative channel for transmission of radio-burst number 1 for eight different patterns p is listed in Table 24-9. A random channel offset r may be added, to shift the complete pattern within the operating band

dependent on regulatory and implementation needs. The channel number for transmission for a given radio-burst is then given by:

$$ChanNumber(p, l) = C(p, l) \times phyLecimFskSplitChannelMultiplier + r$$

Table 24-9—Eight relative channel patterns p for transmission of radio-burst l on channel $C(l)$

		$C(p, l)$												
		0	1	2	3	4	5	6	7	8	9	10	11	
p	0	5	21	13	6	22	14	1	17	9	0	16	8	
	1	4	20	12	1	17	9	0	16	8	6	22	14	
	2	4	20	12	3	19	11	6	22	14	7	23	15	
	3	6	22	14	2	18	10	7	23	15	0	16	8	
	4	7	23	15	4	20	12	3	19	11	2	18	10	
	5	3	19	11	6	22	14	2	18	10	0	16	8	
	6	3	19	11	1	17	9	5	21	13	7	23	15	
	7	0	16	8	6	22	14	3	19	11	2	18	10	
p		$C(p, l)$												
		12	13	14	15	16	17	18	19	20	21	22	23	
		0	7	23	15	4	20	12	3	19	11	2	18	10
		1	7	23	15	2	18	10	5	21	13	3	19	11
		2	0	16	8	5	21	13	2	18	10	1	17	9
		3	1	17	9	4	20	12	5	21	13	3	19	11
		4	6	22	14	0	16	8	1	17	9	5	21	13
		5	7	23	15	1	17	9	4	20	12	5	21	13
p		$C(p, l)$												
		6	0	16	8	2	18	10	6	22	14	4	20	12
		7	4	20	12	7	23	15	5	21	13	1	17	9

NOTE— $ChanNumber(p, l)$ is identical to channel number in $phyCurrentChannelInfo$.

Which pattern p is chosen shall be pseudo-randomly chosen based on a number R . R shall be derived as depicted in Figure 24-17. With $p(R)$ given by:

$$p(R) = R \bmod 8$$

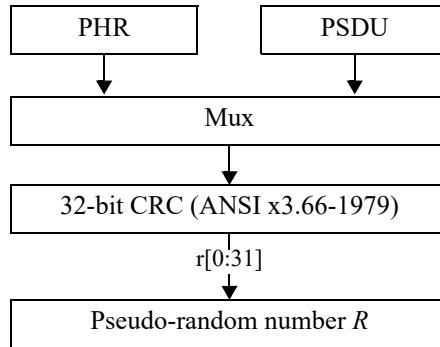


Figure 24-17—Generation of pseudo-random number R

The listed patterns define the time and relative channel for up to 24 radio-bursts. Out of these patterns a consecutive subset of the required number of radio-bursts N_{RB} shall be chosen. The index of the first radio-burst l_0 of the subset is derived from R by:

$$l_0 = R \bmod (24 - N_{\text{RB}} + 1)$$

The first radio-burst shall be transmitted on channel $C(p(R), l_0)$ and the time between the first radio-burst and the next radio-burst is given by $T(p(R), l_0+1)$.

NOTE—This radio-burst distribution method is only suitable for receivers capable of continuously receiving on all channels simultaneously as it has no prior knowledge which pattern was chosen by the transmitter.

24.4.9 Precoding

For each input bit $i[k]$ the output bit $o[k]$ is given by:

$$o[0] = 0 \text{ XOR } i[0], \text{ for } k = 0$$

$$o[k] = i[k-1] \text{ XOR } i[k] \text{ for all } k > 0$$

24.4.10 Spreading

The use of spreading is controlled by the PIB attribute *phyLecimFskSpreading*, as defined in 12.3.5. The SF can be 1, 2, 4, 8, or 16. The variable SF is indicated by the PIB attribute *phyFskSpreadingFactor*, as defined in 12.3.10.

For spreading, a single input bit (b_0) is mapped into the spreading bits $(c_0, c_1, \dots, c_{SF-1})$, as shown in Figure 24-18, and its mapping is represented in Table 24-10.



Figure 24-18—Spreading function

Table 24-10—Input bit to spreading bits mapping

<i>phyFskSpreadingPattern</i>	Spreading factor (SF)	Input bit ($b_0 = 0$)	Input bit ($b_0 = 1$)
ALTERNATING_1/0	2	$(c_0, c_1) = 01$	$(c_0, c_1) = 10$
ALTERNATING_1/0	4	$(c_0, \dots, c_3) = 0101$	$(c_0, \dots, c_3) = 1010$
ALTERNATING_1/0	8	$(c_0, \dots, c_7) = 0101\ 0101$	$(c_0, \dots, c_7) = 1010\ 1010$
ALTERNATING_1/0	16	$(c_0, \dots, c_{15}) = 0101\ 0101\ 0101\ 0101$	$(c_0, \dots, c_{15}) = 1010\ 1010\ 1010\ 1010$
NON_ALTERNATING	2	$(c_0, c_1) = 10$	$(c_0, c_1) = 01$
NON_ALTERNATING	4	$(c_0, \dots, c_3) = 1010$	$(c_0, \dots, c_3) = 0101$
NON_ALTERNATING	8	$(c_0, \dots, c_7) = 1011\ 0001$	$(c_0, \dots, c_7) = 0100\ 1110$
NON_ALTERNATING	16	$(c_0, \dots, c_{15}) = 0010\ 0011\ 1101\ 0110$	$(c_0, \dots, c_{15}) = 1101\ 1100\ 0010\ 1001$

24.5 Data whitening for LECIM FSK PHY

In non-split mode, support for data whitening is optional. In split-mode, data whitening shall always be applied.

The whitened data shall be the exclusive or (XOR) of the input sequence with the PN9 sequence, as described by the following equation:

$$E_n = R_n \oplus \text{PN9}_n$$

where

E_n is the whitened bit

R_n is the data bit being whitened

PN9_n is the PN9 sequence bit

For each packet transmitted with data whitening enabled, R_0 is the first bit of the input sequence, and the index n increments for subsequent bits of the input sequence.

For packets received with the Data Whitening field of the PHR set to one, the receiver decodes the scrambled data in the following way:

$$R_n = RE_n \oplus \text{PN9}_n$$

where

R_n is the bit after de-whitening

RE_n is the input bit of the whitening decoder

The PN generator is defined by the schematic in Figure 24-19.

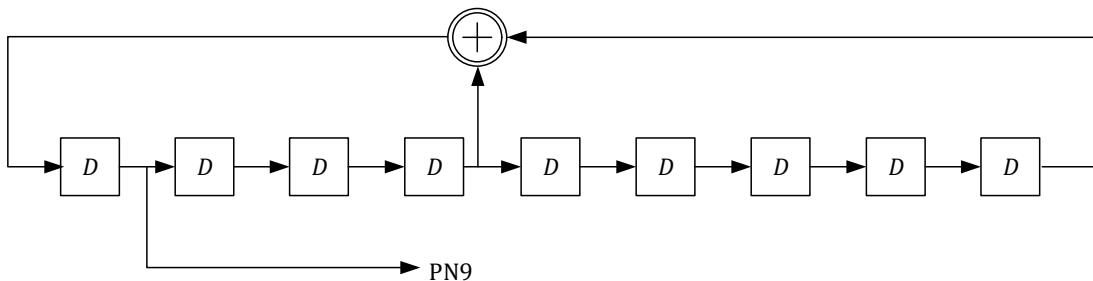


Figure 24-19—Schematic of the PN9 sequence generator

The seed in the PN9 generator shall be all ones: “111111111”. The PN9 generator shall be reinitialized to the seed after each packet (either transmit or receive).

The PN9 generator is clocked using the seed as the starting point and enabled after the first clock cycle. For example, the first 30 bits out of the PN9 generator, once it is enabled, would be as follows:

$$\text{PN9}_n = 0_0, 0_1, 0_2, 0_3, 1_4, 1_5, 1_6, 1_7, 0_8, 1_9, 1_{10}, 1_{11}, 0_{12}, 0_{13}, 0_{14}, 0_{15}, 1_{16}, 0_{17}, 1_{18}, 1_{19}, 0_{20}, 0_{21}, 1_{22}, 1_{23}, 0_{24}, 1_{25}, 1_{26}, 0_{27}, 1_{28}, 1_{29}.$$

24.6 PSDU fragmentation

PSDU fragmentation may be used as described in 23.3.

24.7 LECIM FSK PHY RF requirements

24.7.1 Operating frequency range

The LECIM FSK PHY operates in the bands given in Table 11-3.

24.7.2 Radio frequency tolerance

In non-split mode, the clock radio frequency tolerance shall be within $\pm 10 \times 10^{-6}$.

In split mode, the selected band's highest frequency shall be matched with an accuracy better than $\pm 20 \times 10^{-6}$.

The channel center frequency *ChanCenterFreq*, as defined in 11.1.3.11.3, between any two occupied channels shall satisfy the following:

$$|i - j| \times \text{ChanSpacing} - |f_i - f_j| < 20 \text{ Hz}; \forall i, j \in \{C_{\min}, C_{\min} + 1, \dots, C_{\max}\}$$

where

- i, j are the channel numbers of channel i and j
- ChanSpacing* is the separation between adjacent channels (*phyLecimChannelSpacing*)
- f_i, f_j are the measured center frequencies of channels with channel number i and j

C_{\min}	is the channel number of the lowest channel used for the radio-burst distribution of one transmission
C_{\max}	is the channel number of the highest channel used for the radio-burst distribution of one transmission

24.7.3 Channel switch time

Channel switch time shall be less than or equal to 500 μ s. The channel switch time is defined as the time elapsed at the antenna between the trailing edge of the last symbol of one PPDU to the leading edge of the first symbol of a consecutive PPDU sent on a different channel.

24.7.4 Transmit spectral mask

Implementers are responsible for ensuring that the transmit spectral content conforms to all local regulations.

24.7.5 Receiver sensitivity

Under the conditions specified in 11.1.8, a compliant device shall be capable of achieving a sensitivity of -97 dBm or better in non-split mode.

In split mode, a compliant device shall be capable of achieving at least a sensitivity S as given by:

$$S = -125 \text{ dBm} + 10 \times \log_{10} \left(\frac{\text{Symbol rate}}{SF \times lecimBaseMultiplier} \right) \text{ dB}$$

where SF is the spreading factor.

24.7.6 TX-to-RX turnaround time

The LECIM FSK PHY shall meet the requirements for TX-to-RX turnaround time as defined in 11.2.2.

24.7.7 RX-to-TX turnaround time

The LECIM FSK PHY shall meet the requirements for RX-to-TX turnaround time as defined in 11.2.3.

24.7.8 Transmit power

A compliant device shall be capable of transmitting with a power greater than or equal to -3 dBm. The maximum transmit power is limited by local regulatory bodies.

24.7.9 CCA

After successful completion of the CSMA-CA algorithm as stated in 6.3.2.1, the first radio-burst shall be transmitted. For all subsequent radio-bursts of this transmission, the CCA shall be performed as per 11.2.8, with the CCA Mode as indicated by *phyCcaMode*, for each radio-burst l individually on the channel assigned to radio-burst l . If the channel is assessed to be busy, radio-burst l shall not be transmitted. The time and channel of the subsequent radio-bursts shall stay as if the radio-burst l would have been transmitted.

25. TVWS-FSK PHY

25.1 PPDU format for TVWS-FSK

25.1.1 General

The TVWS-FSK PPDU shall support the format shown in Figure 25-1.

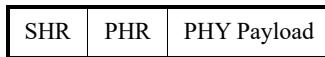


Figure 25-1—Format of the TVWS-FSK PPDU

An example of encoding a TVWS-FSK packet can be found in Seibert [B30].

25.1.2 SHR field format

25.1.2.1 General

The SHR field shall be formatted as illustrated in Figure 25-2.

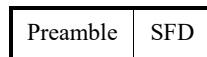


Figure 25-2—Format of the SHR

25.1.2.2 Preamble field format

The Preamble field shall contain *phyFskPreambleLength*, as defined in 12.3.10, multiples of the 8-bit sequence “01010101”. For the purposes of calculating the Ack frame timing required in 6.6.4, the default length of the Preamble field shall be 8 octets.

25.1.2.3 SFD field format

The SFD shall be a 16-bit sequence or, optionally, a 24-bit sequence selected from the values shown in Table 25-1. The SFD length is controlled by the PHY PIB attribute *phyTvwsFskSfdLength*, as defined in 12.3.8.

Devices that do not support FEC, as described in 25.3, shall support the SFD associated with uncoded (PHR + PSDU). Devices that support FEC shall support both SFD values shown in Table 25-1.

Table 25-1—TVWS-FSK SFD values

<i>phyTvwsFskSfdLength</i>	SFD value for coded (PHR + PSDU)	SFD value for uncoded (PHR + PSDU)
16 bits	0110 1111 0100 1110	1001 0000 0100 1110
24 bits	1100 0001 1000 1000 1101 0110	1000 0101 1111 1100 1011 0011

25.1.3 PHR field format

The format of the PHR field is shown in Figure 25-3.

Bits: 0	1	2	3	4	5–15
Reserved	Ranging	Parity Check	FCS Type	Data Whitening	Frame Length

Figure 25-3—Format of the PHR for TVWS-FSK

The Ranging field shall be set to one when ranging is used, and zero when it is not.

The Parity Check field shall be computed from the modulo-2 addition of all bits in the PHR other than the Parity Check.

The FCS Type field indicates the length of the FCS field described in 7.2.11 that is included in the MPDU. Table 25-2 shows the relationship between the contents of the FCS Type field and the length of the transmitted FCS.

Table 25-2—Relationship between FCS Type field and FCS field length for TVWS-FSK

FCS Type field value	FCS field length
0	4 octets
1	2 octets

The Data Whitening field indicates whether data whitening of the PSDU is used upon transmission. When data whitening is used, the Data Whitening field shall be set to one. It shall be set to zero otherwise. Data whitening shall only be applied to the PSDU.

The Frame Length field is an unsigned integer that shall be set to the total number of octets contained in the PSDU (prior to FEC encoding, if enabled). The Frame Length field shall be transmitted MSB first.

25.1.4 PHY Payload field

The PHY Payload field carries the encoded PSDU.

25.2 Modulation and coding for TVWS-FSK

25.2.1 General

The modulation for the TVWS-FSK PHY is 2-level FSK or 4-level FSK, depending on the operating mode. Table 25-3 shows the modulation and channel parameters for the operating modes of the TVWS-FSK PHY.

Table 25-3—TVWS-FSK modulation and channel parameters^a

Parameter	Mode #1		Mode #2		Mode #3		Mode #4	Mode #5
Data rate (kb/s)	50		100		200		300	400
Modulation level	2-level		2-level		2-level		2-level	4-level
Modulation index h	0.5	1.0	0.5	1.0	0.5	1.0	0.5	0.33
Channel spacing (kHz)	100	200	200	400	400	600	600	600

^a Data rates shown are over-the-air data rates (the data rates transmitted over the air regardless of whether the FEC is enabled).

25.2.2 Reference modulator

The functional block diagram of the reference modulator in Figure 25-4 is provided as a reference for specifying the TVWS-FSK data flow processing functions.

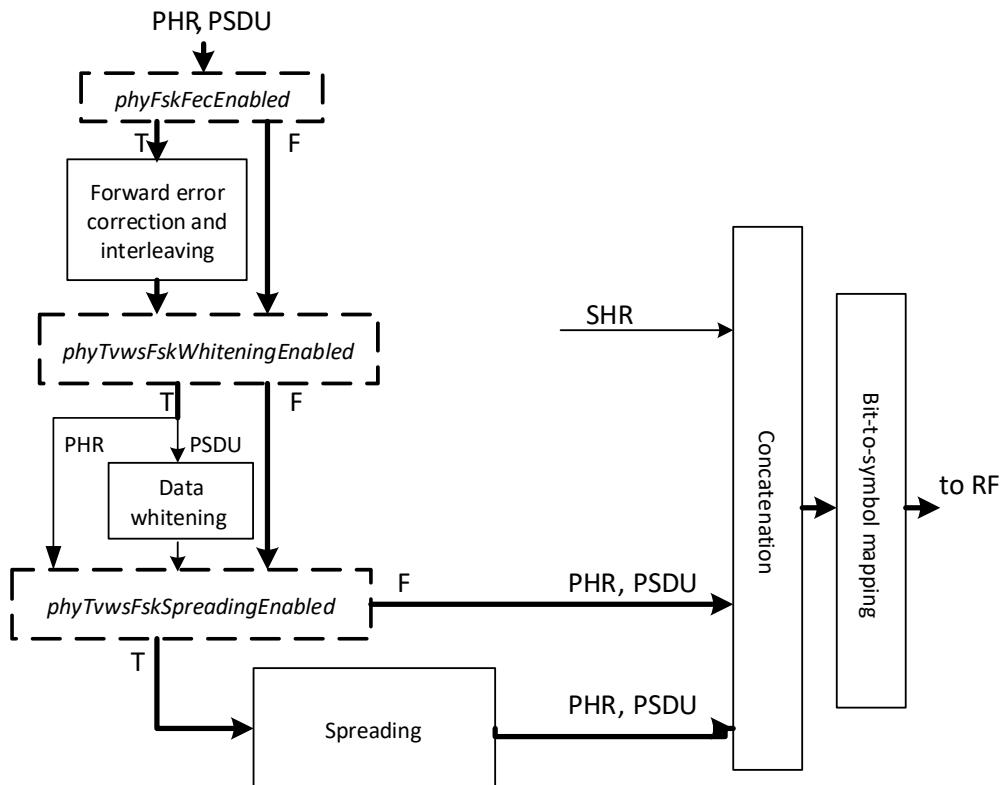


Figure 25-4—Reference modulator diagram for TVWS-FSK

25.2.3 FEC and interleaving

FEC support is optional. The use of FEC is controlled by the PHY PIB attribute *phyFskFecEnabled*, as defined in 12.3.10. Three FEC schemes are included. The FEC scheme is controlled by the PHY PIB attribute *phyTvwsFskFecScheme* as defined in 12.3.8. The first FEC scheme shall be according to 24.4.5.2. For this scheme, interleaving shall always be used when FEC is enabled, and the interleaving scheme shall

be as defined in 24.4.6. The second FEC scheme shall be according to the RSC FEC scheme defined in 20.3.5. For this scheme, interleaving shall be controlled by the value of the *phyFskFecInterleavingRsc* PHY PIB attribute. The third FEC scheme shall be according to the NRNSC FEC scheme defined in 20.3.5. For this scheme, interleaving shall always be used when FEC is enabled, and the interleaving scheme shall be as defined in 20.3.6.

25.2.4 Data whitening

Data whitening is optional. The use of data whitening is controlled by the PIB attribute *phyTvwsFskWhiteningEnabled*, as defined in 12.3.8. The data whitening algorithm shall be as defined in 24.5.

25.2.5 Spreading

Spreading support is optional. The use of spreading is controlled by the PIB attribute *phyTvwsFskSpreadingEnabled*, as defined in 12.3.8. The spreading method shall be as defined in 24.4.10.

25.2.6 Bit-to-symbol mapping

The symbol encoding for 2-level FSK is shown in Table 25-4.

Table 25-4—2-level TVWS-FSK symbol encoding

Symbol (binary)	Frequency deviation
0	$-f_{\text{dev}}$
1	$+f_{\text{dev}}$

The symbol encoding for 4-level FSK is shown in Table 25-5.

Table 25-5—4-level TVWS-FSK symbol encoding

Symbol (binary)	Frequency deviation
01	$-f_{\text{dev}}$
00	$-f_{\text{dev}}/3$
10	$+f_{\text{dev}}/3$
11	$+f_{\text{dev}}$

- For 2-level FSK, the frequency deviation, f_{dev} , is equal to $(\text{symbol rate} \times \text{modulation index})/2$.
- For 4-level FSK, the frequency deviation, f_{dev} , is equal to $(3 \times \text{symbol rate} \times \text{modulation index})/2$. Two bits shall be mapped to four frequency deviation levels for the PHR and PSDU.

The SHR shall always be encoded using 2-level modulation as specified in Table 25-4.

25.2.7 Modulation quality

The modulation quality shall be as given in 20.3.4.

25.2.8 Values for *phySymbolsPerOctet*

The values for *phySymbolsPerOctet* are as follows:

- For 2-level modulation and *phyFskFecEnabled* = FALSE, *phySymbolsPerOctet* = 8.
- For 4-level modulation and *phyFskFecEnabled* = FALSE, *phySymbolsPerOctet* = 4.
- For 2-level modulation and *phyFskFecEnabled* = TRUE, *phySymbolsPerOctet* = 16.
- For 4-level modulation and *phyFskFecEnabled* = TRUE, *phySymbolsPerOctet* = 8.

25.3 TVWS-FSK RF requirements

25.3.1 Operating frequency range

The TVWS-FSK PHY operates in the bands indicated in Table 10-47.

25.3.2 Clock frequency and timing accuracy

The clock frequency and time accuracy shall be within $\pm 20 \times 10^{-6}$.

25.3.3 Channel switch time

The channel switch time shall be as given in 24.7.3.

25.3.4 Receiver sensitivity

The receiver sensitivity shall be as given in 20.6.7.

25.3.5 TX-to-RX turnaround time

The TX-to-RX turnaround time shall be as given in 20.6.9.

25.3.6 RX-to-TX turnaround time

The RX-to-TX turnaround time shall be as given in 20.6.10.

25.3.7 Receiver maximum input level of desired signal

The TVWS-FSK PHY shall have a receiver maximum input level greater than or equal to -20 dBm using the measurement defined in 11.2.5.

25.3.8 Receiver ED

The TVWS-FSK PHY shall provide the receiver ED measurement as described in 11.2.6.

25.3.9 LQI

The TVWS-FSK PHY shall provide the LQI measurement as described in 11.2.7.

26. TVWS-OFDM PHY

26.1 General

For the purposes of calculating the Ack frame timing required in 6.6.4, the default STF shall have two repetitions.

26.2 PPDU format for TVWS-OFDM

26.2.1 General

The TVWS-OFDM PPDU shall be formatted as illustrated in Figure 26-1.

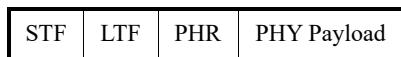


Figure 26-1—Format of the TVWS-OFDM PPDU

The PHY Payload field shall be formatted as illustrated in Figure 26-2.



Figure 26-2—Format of the PHY Payload field

An example of encoding a TVWS-OFDM packet can be found in Shin, et al. [B31].

26.2.2 STF

26.2.2.1 Frequency domain STF

Table 26-1 shows the frequency domain representation of the STF.

Table 26-1—Frequency domain representation of STF for TVWS-OFDM

Tone #	Value	Tone #	Value	Tone #	Value	Tone #	Value
-64	0	-32	$\sqrt{2} + \sqrt{2}j$	0	0	32	$\sqrt{2} + \sqrt{2}j$
-63	0	-31	0	1	0	33	0
-62	0	-30	0	2	0	34	0
-61	0	-29	0	3	0	35	0
-60	0	-28	0	4	0	36	0
-59	0	-27	0	5	0	37	0
-58	0	-26	0	6	0	38	0
-57	0	-25	0	7	0	39	0
-56	0	-24	$-\sqrt{2} - \sqrt{2}j$	8	$-\sqrt{2} - \sqrt{2}j$	40	$\sqrt{2} + \sqrt{2}j$
-55	0	-23	0	9	0	41	0
-54	0	-22	0	10	0	42	0

Table 26-1—Frequency domain representation of STF for TVWS-OFDM (continued)

Tone #	Value	Tone #	Value	Tone #	Value	Tone #	Value
-53	0	-21	0	11	0	43	0
-52	0	-20	0	12	0	44	0
-51	0	-19	0	13	0	45	0
-50	0	-18	0	14	0	46	0
-49	0	-17	0	15	0	47	0
-48	$\sqrt{2} + \sqrt{2}j$	-16	$-\sqrt{2} - \sqrt{2}j$	16	$-\sqrt{2} - \sqrt{2}j$	48	$\sqrt{2} + \sqrt{2}j$
-47	0	-15	0	17	0	49	0
-46	0	-14	0	18	0	50	0
-45	0	-13	0	19	0	51	0
-44	0	-12	0	20	0	52	0
-43	0	-11	0	21	0	53	0
-42	0	-10	0	22	0	54	0
-41	0	-9	0	23	0	55	0
-40	$-\sqrt{2} - \sqrt{2}j$	-8	$\sqrt{2} + \sqrt{2}j$	24	$\sqrt{2} + \sqrt{2}j$	56	0
-39	0	-7	0	25	0	57	0
-38	0	-6	0	26	0	58	0
-37	0	-5	0	27	0	59	0
-36	0	-4	0	28	0	60	0
-35	0	-3	0	29	0	61	0
-34	0	-2	0	30	0	62	0
-33	0	-1	0	31	0	63	0

26.2.2.2 Time domain STF generation

Given a sequence of 128 samples $f(n)$, indexed by $n = 0, \dots, 127$, the DFT is defined as $F(k)$, where $k = 0, \dots, 127$:

$$F(k) = \frac{1}{\sqrt{128}} \sum_{n=0}^{127} f(n) e^{-j2\pi kn/128}$$

The sequence $f(n)$ can be calculated from $F(k)$ using the IDFT, where the k values numbered from 0 to 63 correspond to tones numbered from 0 to 63 and the k values numbered from 64 to 127 correspond to tones numbered from -64 to -1, respectively:

$$f(n) = \frac{1}{\sqrt{128}} \sum_{k=0}^{127} F(k) e^{j2\pi nk/128}$$

The time domain STF is obtained as follows:

$$STF_time = IDFT(STF_freq)$$

where STF_freq is given in Table 26-1.

The CP is then prepended to the TVWS-OFDM symbol.

26.2.2.3 Time domain STF repetition

There are 10 repetitions of sync sequence in each STF TVWS-OFDM symbol. The number of STF TVWS-OFDM symbols varies from 1 to 4.

26.2.2.4 STF power boosting

Power boosting shall be applied to the STF TVWS-OFDM symbols in order to aid preamble detection. The boost shall be a multiplication by 2.

26.2.3 LTF

26.2.3.1 Frequency domain LTF

Table 26-2 shows the frequency domain representation of the LTF.

Table 26-2—Frequency domain representation of LTF for TVWS-OFDM

Tone #	Value						
-64	0	-32	-1	0	0	32	-1
-63	0	-31	1	1	-1	33	1
-62	0	-30	-1	2	1	34	-1
-61	0	-29	-1	3	-1	35	-1
-60	0	-28	1	4	1	36	1
-59	0	-27	1	5	-1	37	-1
-58	0	-26	-1	6	-1	38	1
-57	0	-25	1	7	-1	39	-1
-56	0	-24	1	8	1	40	-1
-55	0	-23	1	9	-1	41	1
-54	1	-22	1	10	1	42	-1
-53	-1	-21	1	11	-1	43	1
-52	-1	-20	-1	12	-1	44	-1
-51	-1	-19	1	13	-1	45	1
-50	1	-18	1	14	-1	46	1
-49	-1	-17	1	15	-1	47	-1
-48	-1	-16	1	16	1	48	-1

Table 26-2—Frequency domain representation of LTF for TVWS-OFDM (continued)

Tone #	Value						
-47	1	-15	-1	17	-1	49	1
-46	-1	-14	1	18	1	50	1
-45	-1	-13	-1	19	-1	51	1
-44	1	-12	1	20	1	52	1
-43	1	-11	-1	21	1	53	-1
-42	-1	-10	1	22	1	54	1
-41	1	-9	-1	23	-1	55	0
-40	1	-8	-1	24	-1	56	0
-39	1	-7	1	25	1	57	0
-38	1	-6	-1	26	-1	58	0
-37	-1	-5	1	27	-1	59	0
-36	-1	-4	-1	28	1	60	0
-35	-1	-3	1	29	-1	61	0
-34	1	-2	-1	30	1	62	0
-33	-1	-1	-1	31	1	63	0

26.2.3.2 Time domain LTF generation

The time domain LTF is obtained as follows:

$$LTF_time = IDFT(LTF_freq)$$

where *LTF_freq* is given in Table 26-2.

The time-domain LTF structure shall be formatted as illustrated in Figure 26-3, where T_{LTF} is the duration of the base symbol.

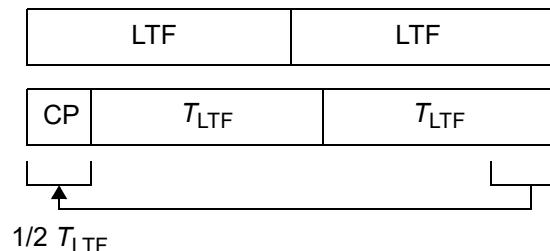


Figure 26-3—Structure of LTF for TVWS-OFDM and TVWS-NB-OFDM

26.2.4 PHR field format

The PHR field shall be formatted as illustrated in Figure 26-4.

Bits: 0–4	5	6–7	8–18	19–27	28–43	44–49
Reserved	Ranging	Rate	Frame Length	Scrambling Seed	HCS	PHR Tail

Figure 26-4—PHY field format for TVWS-OFDM

The PHR field occupies one TVWS-OFDM symbol. The PHR shall be transmitted using the lowest supported MCS level, as described in Table 26-3.

The Ranging field shall be set to one to indicate that this particular frame is intended for ranging. If the frame is not intended for ranging, the Ranging field shall be set to zero.

The Rate field specifies the data rate of the payload and is equal to the numerical value of the MCS for the mandatory mode and the numerical value of the MCS minus three for the optional 4 times overclock modes, as described in 26.3, transmitted MSB first. The data rates for TVWS-OFDM can be found in 26.3.

The Frame Length field is an unsigned integer that shall be set to the total number of octets contained in the PSDU (prior to FEC encoding). The Frame Length field shall be transmitted MSB first.

The Scrambler field specifies the scrambling seed defined by the manufacturer.

The HCS field is a 16-bit CRC taken over the PHR fields. The HCS shall be computed using the first 28 bits of the PHR. The HCS shall be calculated using the polynomial $G_{16}(x) = x^{16} + x^{12} + x^5 + 1$.

The HCS is the one's complement of the modulo 2 sum of the two remainders in a) and b):

- a) The remainder resulting from $[x^k(x^{15} + x^{14} + \dots + 1)]$ divided (modulo 2) by $G_{16}(x)$, where the value k is the number of bits in the calculation field.
- b) The remainder resulting from the calculation field contents, treated as a polynomial, multiplied by x^{16} and then divided (modulo 2) by $G_{16}(x)$.

At the transmitter, the initial remainder of the division shall be preset to all ones and then be modified via division of the calculation field by the generator polynomial, $G_{16}(x)$. The one's complement of this remainder is the HCS field. The coefficient of the highest order term shall be transmitted first.

The PHR Tail field, which consists of all zeros, is for Viterbi decoder flushing, as described in 26.4.7.

26.2.5 PSDU field

The PSDU field carries the encoded PSDU.

26.3 System parameters for TVWS-OFDM

For devices that support the TVWS-OFDM PHY, modes MCS0, MCS1, and MCS2 shall be supported, and modes MCS3, MCS4, and MCS5 are optional, as shown in Table 26-3.

The system parameters for the TVWS-OFDM PHY are shown in Table 26-3. Included in Table 26-3 are the data rates and the number of symbols per octet, which depend on both the MCS level and the TVWS-OFDM

Mode. The nominal bandwidth is calculated by multiplying {the number of active tones + 1 for the DC tone} by {the subcarrier spacing}.

Table 26-3—System parameters for TVWS-OFDM

Parameter	Mandatory modes ^a	Optional modes
Nominal bandwidth (kHz)	1064.5	4258
Subcarrier spacing (kHz)	1250/128	4×1250/128
DFT size	128	128
Active tones	108	108
# Pilot tones	8	8
# Data tones	100	100
MCS0 (BPSK)	Data Rate (kb/s)	390.625
	<i>phySymbolsPerOctet</i>	8 bits/octet × 1/50 symbol/bits
MCS1 (QPSK)	Data Rate (kb/s)	781.250
	<i>phySymbolsPerOctet</i>	8 bits/octet × 1/100 symbol/bits
MCS2 (16-QAM)	Data Rate (kb/s)	1562.5
	<i>phySymbolsPerOctet</i>	8 bits/octet × 1/200 symbol/bits
MCS3 (BPSK)	Data Rate (kb/s)	—
	<i>phySymbolsPerOctet</i>	—
MCS4 (QPSK)	Data Rate (kb/s)	—
	<i>phySymbolsPerOctet</i>	—
MCS5 (16-QAM)	Data Rate (kb/s)	—
	<i>phySymbolsPerOctet</i>	—

^a For devices that support the TVWS-OFDM PHY.

26.4 Modulation and coding for TVWS-OFDM

26.4.1 Reference modulator

The reference modulator is illustrated in Figure 26-5.

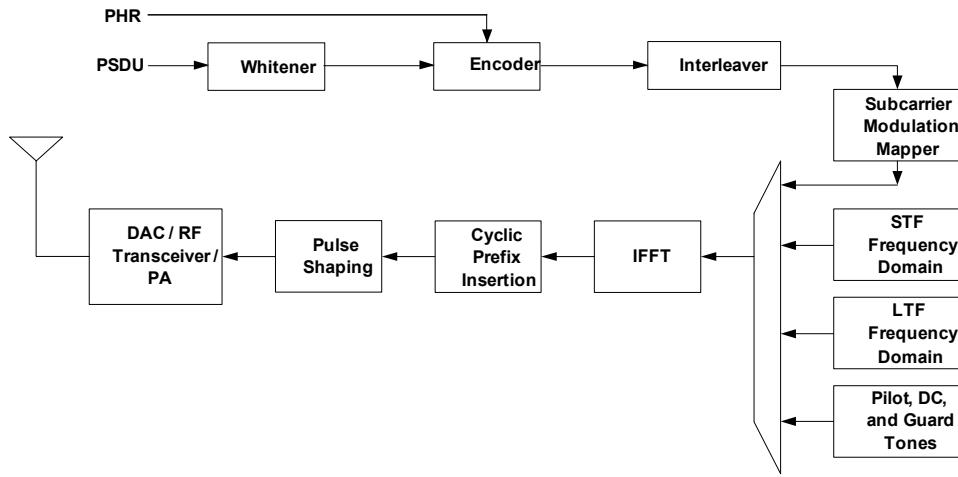


Figure 26-5—Reference modulator diagram for TVWS-OFDM

26.4.2 Bit-to-symbol mapping

Figure 26-6 shows the bit-to-symbol mapping for BPSK, QPSK, and 16-QAM.

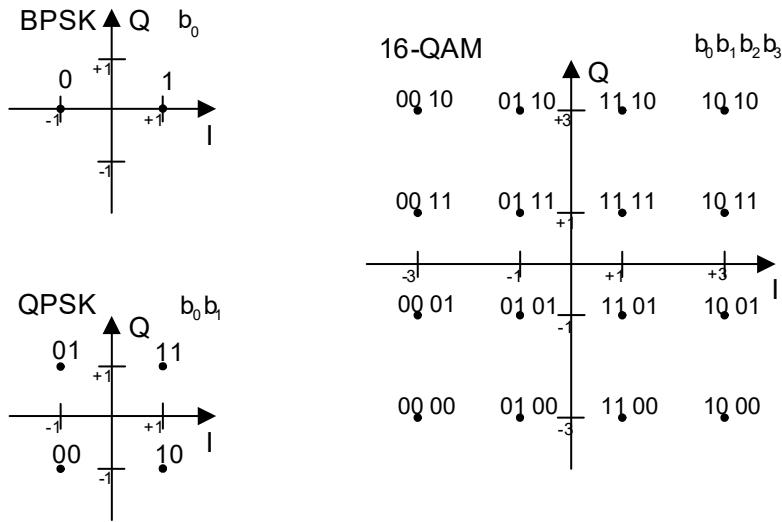


Figure 26-6—Bit-to-symbol mapping for TVWS-OFDM

The output values, d , are formed by multiplying the resulting $(I + jQ)$ value by a normalization factor K_{MOD} :

$$d = (I + jQ) \times K_{\text{MOD}}$$

The normalization factor, K_{MOD} , depends on the base modulation mode, as described in Table 26-4. The purpose of the normalization factor is to achieve the same average power for all mappings.

Table 26-4—Modulation-dependent normalization factor K_{MOD} for TVWS-OFDM

Modulation	K_{MOD}
BPSK	1
QPSK	$1/\sqrt{2}$
16-QAM	$1/\sqrt{10}$

26.4.3 FEC

The DATA field shall be coded with a convolutional encoder of coding rate $R = 1/2$. The DATA field consists of the PHR field when encoding the PHY header as shown in Figure 26-4. The DATA field consists of the PSDU field, PPDU Tail field, and Pad field as shown in Figure 26-1 when encoding the remainder of the PPDU. The convolutional encoder shall use the generator polynomials expressed in octal representation, $g_0 = 133_8$ and $g_1 = 171_8$, of rate $R = 1/2$, as shown in Figure 26-7. The convolutional encoder shall be initialized to the all-zeros state before encoding the PHR and then reset to the all-zeros state before encoding the PSDU.

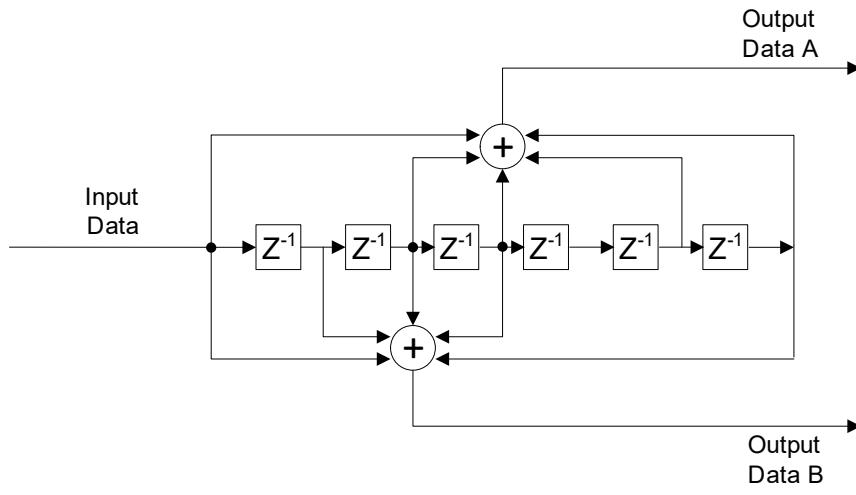


Figure 26-7—Rate 1/2 convolutional encoder for TVWS-OFDM

The first coded bit is from Output Data A, and the second coded bit is from Output Data B.

26.4.4 Interleaver

The interleaving process consists of two permutations. The index of the coded bit before the first permutation shall be denoted as k ; i shall be the index after the first and before the second permutation; and j shall be the index after the second permutation, just prior to modulation mapping. The coded bits are written at the index given by j and read out sequentially. The index i is defined as follows:

$$i = \left(\frac{N_{\text{cbps}}}{N_{\text{row}}} \right) \times [k \bmod(N_{\text{row}})] + \text{floor} \left(\frac{k}{N_{\text{row}}} \right)$$

where

N_{cbps} is the number of coded bits per symbol

k is $0, 1, 2, \dots, (N_{\text{cbps}} - 1)$

N_{row} is 20

The process of interleaving for the first permutation is illustrated in Figure 26-8.

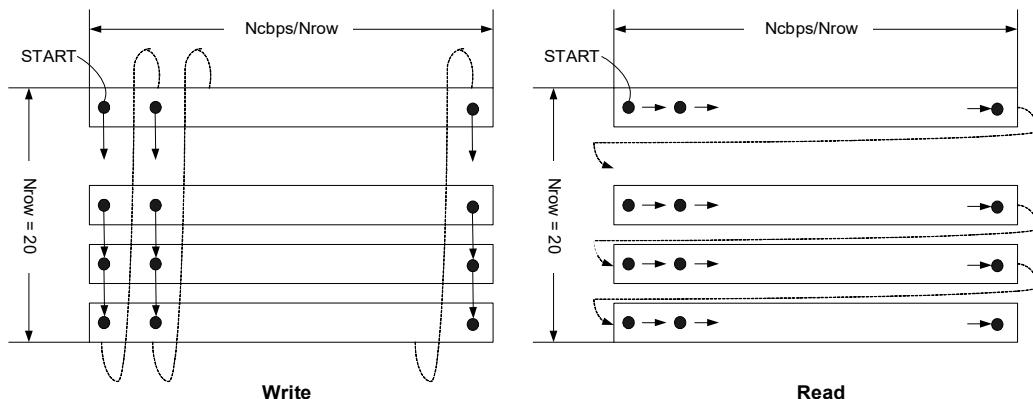


Figure 26-8—The process of interleaving for the first permutation

The index j is defined as follows:

$$j = s \times \text{floor}\left(\frac{i}{s}\right) + \left[i + N_{\text{cbps}} - \text{floor}\left(\frac{N_{\text{row}} \times i}{N_{\text{cbps}}}\right)\right] \bmod(s)$$

where

N_{cbps} is the number of coded bits per symbol

i is $0, 1, 2, \dots, (N_{\text{cbps}} - 1)$

N_{row} is 20

and

$$s = \max\left(\frac{N_{\text{bpsc}}}{2}, 1\right)$$

where N_{bpsc} is the number of bits per subcarrier and has the values 1, 2, and 4 for BPSK, QPSK, and 16-QAM, respectively. N_{cbps} is defined as follows: 100 bits for BPSK, 200 bits for QPSK, and 400 bits for 16-QAM.

26.4.5 Pilot tones/null tones

The numbers of pilot and null tones for TVWS-OFDM are defined as shown in Table 26-5.

Table 26-5—Number of pilot and null tones for TVWS-OFDM

Tone	Mandatory modes	Optional modes
Active tones	108	108
# Pilot tones	8	8
# Data tones	100	100
# DC null tones	1	1

The DC tone is numbered as 0, and the subcarriers for pilot and data tones are numbered as -54 to 54 with the DC tone unused as depicted in Figure 26-9.

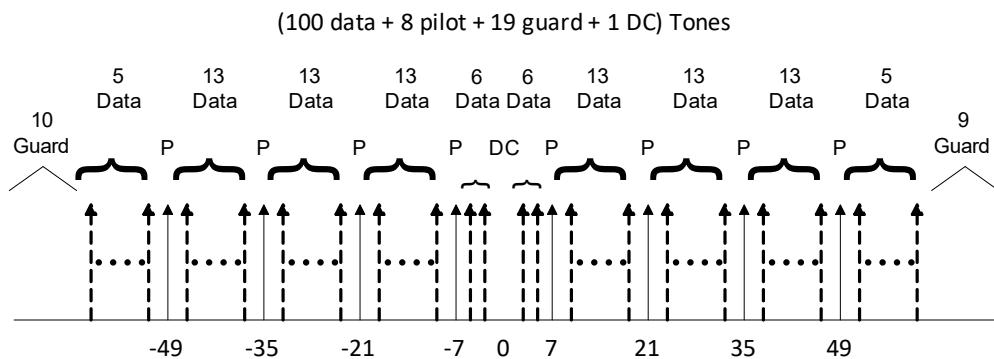


Figure 26-9—Pilot tones for TVWS-OFDM

The first output symbol is mapped to the most negative data carrier index in data tones, and the second output symbol is mapped to the second most negative data carrier index in data tones, and so on. The data carried on the pilot tones shall be determined by a PN9 pseudo-noise sequence, generated by the PN9 sequence generator shown in Figure 17-2, with the seed “11111111”. The first output bit is assigned to the most negative index in pilot tones. For example, the first output bit from the PN9 sequence is assigned to the pilot symbol with index -49 , and the second output bit is assigned to the pilot symbol with index -35 , and so on. Table 26-6 shows the mapping from PN9 bits to the pilot BPSK symbols for all MCS levels. Index n starts after the LTF from zero and is increased by one for every pilot subcarrier.

Table 26-6—Mapping from PN9 sequence to pilot BPSK symbols for TVWS-OFDM

Input bit (PN9_n)	BPSK symbol
0	$-1 + (0 \times j)$
1	$1 + (0 \times j)$

26.4.6 CP

For the STF, the CP is defined in 26.2.2.3. For the LTF, the CP is defined in 26.2.3.2. For the remaining TVWS-OFDM symbols, a CP shall be prepended to each base symbol. The duration of the CP (25.6 μ s) shall be 1/4 of the base symbol (102.4 μ s).

26.4.7 PPDU Tail field

The PPDU Tail field shall be six bits of 0, which are required to return the convolutional encoder to the *zero state*. This procedure reduces the error probability of the convolutional decoder, which relies on future bits when decoding and which may not be available past the end of the message. The PPDU Tail field shall be produced by replacing six scrambled zero bits following the message end with six non-scrambled zero bits.

26.4.8 Pad field

The number of bits in the DATA field shall be a multiple of N_{cbps} . To achieve that, the length of the message is extended so that it becomes a multiple of N_{dbps} , the number of data bits per TVWS-OFDM symbol. At least six bits are appended to the message, in order to accommodate the PPDU Tail field, as described in 26.4.7. The number of TVWS-OFDM symbols, N_{SYM} , the number of bits in the DATA field, N_{DATA} , and the number of pad bits, N_{PAD} , are computed using the length, in octets, of the PSDU (the LENGTH is equal to the content of the Frame Length field in Figure 26-4) as follows:

$$N_{\text{dbps}} = N_{\text{cbps}} \times R$$

$$N_{\text{SYM}} = \text{ceiling}[(8 \times \text{LENGTH} + 6)/N_{\text{dbps}}]$$

$$N_{\text{DATA}} = N_{\text{SYM}} \times N_{\text{dbps}}$$

$$N_{\text{PAD}} = N_{\text{DATA}} - (8 \times \text{LENGTH} + 6)$$

The function ceiling() returns the smallest integer value greater than or equal to its argument value. The appended bits (i.e., pad bits) are set to zeros and are subsequently scrambled with the rest of the bits in the DATA field.

In the case where the DATA field consists of the PHR, the number of bits in the DATA field (PHR as shown in 26.2.4) shall be set to 50.

26.4.9 Scrambler and scrambler seeds

The input to the scrambler is the data bits followed by PPDU Tail field and then the Pad field. The scrambler uses a PN9 sequence that is generated by the generator shown in Figure 17-2. The PN9 scrambler is initialized by the scrambling seed specified by 9 bits in the PHR, as shown in Figure 26-4. The leftmost value of the scrambling seed is placed into the leftmost delay element in Figure 17-2. The PN9 generator is clocked using the seed as the starting point and enabled after the first clock cycle. The PN9 generator shall be reinitialized to the seed after each packet (either transmit or receive).

26.5 TVWS-OFDM RF requirements

26.5.1 Operating frequency range

The TVWS-OFDM PHY operates in the bands indicated in Table 10-47.

26.5.2 Pulse shaping

Pulse shaping shall be applied at the transmitter using a filter equivalent to the root raised cosine filter with a roll-off factor of 0.5. The parameters of the filter shall be as needed to meet regulatory requirements in the band of operation. It is recommended that the receiver also use a filter equivalent to the root raised cosine filter with a roll-off factor of 0.5.

26.5.3 Transmit power spectral density (PSD) mask

The TVWS-OFDM PHY transmit PSD mask shall conform with local regulations.

26.5.4 Receiver sensitivity

The sensitivity requirements, as described in 11.1.8, for every option and MCS mode are shown in Table 26-7.

Table 26-7—TVWS-OFDM PHY sensitivity requirements

MCS mode	Sensitivity
0	-97 dBm
1	-94 dBm
2	-88 dBm
3	-91 dBm
4	-88 dBm
5	-82 dBm

26.5.5 TX-to-RX turnaround time

The TX-to-RX turnaround time shall be as given in 11.2.2.

26.5.6 RX-to-TX turnaround time

The RX-to-TX turnaround time shall be as given in 11.2.3.

26.5.7 EVM definition

The relative constellation RMS error averaged over subcarriers, symbols, and packets shall not exceed the values shown in Table 26-8.

Table 26-8—TVWS-OFDM PHY EVM requirements

MCS mode	RMS error	
	Mandatory modes	Optional modes
0	-10 dB	—
1	-10 dB	—
2	-16 dB	—
3	—	-10 dB
4	—	-10 dB
5	—	-16 dB

The transmit modulation accuracy test shall be performed by instrumentation capable of converting the transmitted signal into a stream of complex samples. The sampled signal shall be processed in a manner similar to an actual receiver, according to the following steps, or an equivalent procedure:

- a) Detect the start of packet.
- b) Detect the transition from STF to LTF, and establish fine timing (with one sample resolution).
- c) Estimate the coarse and fine frequency offsets.
- d) De-rotate the packet according to estimated frequency offset.
- e) Estimate the complex channel response coefficients for each of the subcarriers.
- f) For each data TVWS-OFDM symbol, transform the symbol into subcarrier received values, and divide each subcarrier value with the estimated channel response coefficient.
- g) For each data-carrying subcarrier, find the closest constellation point, and compute the squared Euclidean distance from it.
- h) Compute the RMS average of all errors in a packet:

$$RMS_{\text{error}} = 20 \log_{10} \left(\frac{1}{N_F} \sum_{i=1}^{N_F} \sqrt{\frac{\sum_{j=1}^{N_{\text{SYM}}} \sum_{k \in U_D} \Delta(i,j,k)^2}{100 \times N_{\text{SYM}} \times P_0}} \right)$$

with

$$\Delta(i,j,k)^2 = [I(i,j,k) - I_0(i,j,k)]^2 + [Q(i,j,k) - Q_0(i,j,k)]^2$$

where

N_{SYM} is the number of TVWS-OFDM symbols in the packet

N_F is the number of packets used for the measurement

U_D is the index set of data tones

$[I_0((i,j,k),Q_0(i,j,k))]$ denotes the ideal symbol point of the i th packet, j th TVWS-OFDM symbol of the packet, and k th subcarrier of the TVWS-OFDM symbol in the complex plane

$[I((i,j,k),Q(i,j,k))]$ denotes the observed point of the i th packet, j th TVWS-OFDM symbol of the packet, and k th tone of the TVWS-OFDM symbol in the complex plane

P_0 is the average power of the constellation

The test shall be performed over at least $N_F = 20$ packets. The payload of the packets under test shall contain $N_{\text{SYM}} = 16$ TVWS-OFDM symbols. Random data shall be used for the payload.

26.5.8 Transmit center frequency and symbol tolerance

The transmit center frequency tolerance shall be $\pm 20 \times 10^{-6}$ maximum. The symbol clock frequency tolerance shall also be $\pm 20 \times 10^{-6}$ maximum. The transmit center frequency and the symbol clock frequency shall be derived from the same reference oscillator.

27. TVWS-NB-OFDM PHY

27.1 PPDU format for TVWS-NB-OFDM

27.1.1 General

The TVWS-NB-OFDM PPDU shall be formatted as illustrated in Figure 27-1.



Figure 27-1—Format of the TVWS-NB-OFDM PPDU

An example of encoding a TVWS-NB-OFDM packet can be found in Lu, et al. [B24].

27.1.2 Short Training field (STF)

27.1.2.1 Frequency domain STF

Table 27-1 shows the frequency domain representation of the STF.

Table 27-1—Frequency domain representation of STF for TVWS-NB-OFDM

Tone #	Re	Im									
-192	-1.4142	-1.4142	-96	-1.4142	-1.4142	0	-1.4142	-1.4142	96	-1.4142	-1.4142
-191	0	0	-95	0	0	1	0	0	97	0	0
-190	0	0	-94	0	0	2	0	0	98	0	0
-189	0	0	-93	0	0	3	0	0	99	0	0
-188	1.6257	1.165	-82	1.165	-1.6257	4	-1.6257	-1.165	100	-1.165	1.6257
-187	0	0	-91	0	0	5	0	0	101	0	0
-186	0	0	-90	0	0	6	0	0	102	0	0
-185	0	0	-89	0	0	7	0	0	103	0	0
-184	-1.9829	-0.2611	-88	1.9829	0.2611	8	-1.9829	-0.2611	104	1.9829	0.2611
-183	0	0	-87	0	0	9	0	0	105	0	0
-182	0	0	-86	0	0	10	0	0	106	0	0
-181	0	0	-85	0	0	11	0	0	107	0	0
-180	1.546	-1.2688	-84	1.2688	1.546	12	-1.546	1.2688	108	-1.2688	-1.546
-179	0	0	-83	0	0	13	0	0	109	0	0
-178	0	0	-82	0	0	14	0	0	110	0	0
-177	0	0	-81	0	0	15	0	0	111	0	0
-176	0.5176	1.9319	-80	0.5176	1.9319	16	0.5176	1.9319	112	0.5176	1.9319
-175	0	0	-79	0	0	17	0	0	113	0	0
-174	0	0	-78	0	0	18	0	0	114	0	0

Table 27-1—Frequency domain representation of STF for TVWS-NB-OFDM (continued)

Tone #	Re	Im									
-173	0	0	-77	0	0	19	0	0	115	0	0
-172	-1.9733	0.3258	-76	0.3258	1.9733	20	1.9733	-0.3258	116	-0.3258	-1.9733
-171	0	0	-75	0	0	21	0	0	117	0	0
-170	0	0	-74	0	0	22	0	0	118	0	0
-169	0	0	-73	0	0	23	0	0	119	0	0
-168	-0.7654	-1.8478	-72	0.7654	1.8478	24	-0.7654	-1.8478	120	0.7654	1.8478
-167	0	0	-71	0	0	25	0	0	121	0	0
-166	0	0	-70	0	0	26	0	0	122	0	0
-165	0	0	-69	0	0	27	0	0	123	0	0
-164	1.165	-1.6257	-68	1.6257	1.165	28	-1.165	1.6257	124	-1.6257	-1.165
-163	0	0	-67	0	0	29	0	0	125	0	0
-162	0	0	-66	0	0	30	0	0	126	0	0
-161	0	0	-65	0	0	31	0	0	127	0	0
-160	1.9319	-0.5176	-64	1.9319	-0.5176	32	1.9319	-0.5176	128	1.9319	-0.5176
-159	0	0	-63	0	0	33	0	0	129	0	0
-158	0	0	-62	0	0	34	0	0	130	0	0
-157	0	0	-61	0	0	35	0	0	131	0	0
-156	1.9904	0.196	-60	0.196	-1.9904	36	-1.9904	-0.196	132	-0.196	1.9904
-155	0	0	-59	0	0	37	0	0	133	0	0
-154	0	0	-58	0	0	38	0	0	134	0	0
-153	0	0	-57	0	0	39	0	0	135	0	0
-152	1.9829	0.2611	-56	-1.9829	-0.2611	40	1.9829	0.2611	136	-1.9829	-0.2611
-151	0	0	-55	0	0	41	0	0	137	0	0
-150	0	0	-54	0	0	42	0	0	138	0	0
-149	0	0	-53	0	0	43	0	0	139	0	0
-148	1.9733	-0.3258	-52	0.3258	1.9733	44	-1.9733	0.3258	140	-0.3258	-1.9733
-147	0	0	-51	0	0	45	0	0	141	0	0
-146	0	0	-50	0	0	46	0	0	142	0	0
-145	0	0	-49	0	0	47	0	0	143	0	0
-144	1.4142	-1.4142	-48	1.4142	-1.4142	48	1.4142	-1.4142	144	1.4142	-1.4142
-143	0	0	-47	0	0	49	0	0	145	0	0
-142	0	0	-46	0	0	50	0	0	146	0	0
-141	0	0	-45	0	0	51	0	0	147	0	0
-140	-0.3258	-1.9733	-44	-1.9733	0.3258	52	0.3258	1.9733	148	1.9733	-0.3258
-139	0	0	-43	0	0	53	0	0	149	0	0

Table 27-1—Frequency domain representation of STF for TVWS-NB-OFDM (continued)

Tone #	Re	Im									
-138	0	0	-42	0	0	54	0	0	150	0	0
-137	0	0	-41	0	0	55	0	0	151	0	0
-136	-1.9829	-0.2611	-40	1.9829	0.2611	56	-1.9829	-0.2611	152	1.9829	0.2611
-135	0	0	-39	0	0	57	0	0	153	0	0
-134	0	0	-38	0	0	58	0	0	154	0	0
-133	0	0	-37	0	0	59	0	0	155	0	0
-132	-0.196	1.9904	-36	-1.9904	-0.196	60	0.196	-1.9904	156	1.9904	0.196
-131	0	0	-35	0	0	61	0	0	157	0	0
-130	0	0	-34	0	0	62	0	0	158	0	0
-129	0	0	-33	0	0	63	0	0	159	0	0
-128	1.9319	-0.5176	-32	1.9319	-0.5176	64	1.9319	-0.5176	160	1.9319	-0.5176
-127	0	0	-31	0	0	65	0	0	161	0	0
-126	0	0	-30	0	0	66	0	0	162	0	0
-125	0	0	-29	0	0	67	0	0	163	0	0
-124	-1.6257	-1.165	-28	-1.165	1.6257	68	1.6257	1.165	164	1.165	-1.6257
-123	0	0	-27	0	0	69	0	0	165	0	0
-122	0	0	-26	0	0	70	0	0	166	0	0
-121	0	0	-25	0	0	71	0	0	167	0	0
-120	0.7654	1.8478	-24	-0.7654	-1.8478	72	-0.7654	1.8478	168	-0.7654	-1.8478
-119	0	0	-23	0	0	73	0	0	169	0	0
-118	0	0	-22	0	0	74	0	0	170	0	0
-117	0	0	-21	0	0	75	0	0	171	0	0
-116	-0.3258	-1.9733	-20	1.9733	-0.3258	76	0.3258	1.9733	172	-1.9733	0.3258
-115	0	0	-19	0	0	77	0	0	173	0	0
-114	0	0	-18	0	0	78	0	0	174	0	0
-113	0	0	-17	0	0	79	0	0	175	0	0
-112	0.5176	1.9319	-16	0.5176	1.9319	80	0.5176	1.9319	176	0.5176	1.9319
-111	0	0	-15	0	0	81	0	0	177	0	0
-110	0	0	-14	0	0	82	0	0	178	0	0
-109	0	0	-13	0	0	83	0	0	179	0	0
-108	-1.2688	-1.546	-12	-1.546	1.2688	84	1.2688	1.546	180	1.546	-1.2688
-107	0	0	-11	0	0	85	0	0	181	0	0
-106	0	0	-10	0	0	86	0	0	182	0	0
-105	0	0	-9	0	0	87	0	0	183	0	0
-104	1.9829	0.2611	-8	-1.9829	-0.2611	88	1.9829	0.2611	184	-1.9829	-0.2611

Table 27-1—Frequency domain representation of STF for TVWS-NB-OFDM (continued)

Tone #	Re	Im	Tone #	Re	Im	Tone #	Re	Im	Tone #	Re	Im
-103	0	0	-7	0	0	89	0	0	185	0	0
-102	0	0	-6	0	0	90	0	0	186	0	0
-101	0	0	-5	0	0	91	0	0	187	0	0
-100	-1.165	1.6257	-4	-1.6257	-1.165	92	1.165	-1.6257	188	1.6257	1.165
-99	0	0	-3	0	0	93	0	0	189	0	0
-98	0	0	-2	0	0	94	0	0	190	0	0
-97	0	0	-1	0	0	95	0	0	191	0	0

27.1.2.2 Time domain STF generation

The short training field sequence is defined based on a Zadoff Chu sequence with length $N = 96$, a prime number $H = 19$, and $n = 0, 1, \dots, N-1$. The short training field sequence $s(n)$ in the time domain is expressed as below:

$$s(n) = e^{jH\pi n^2/N}, n = 0, 1, 2 \dots N-1$$

The DFT of $s(n)$ is defined as $S(k)$, where $k = 0, \dots, N-1$:

$$S(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} s(n) e^{-j2\pi kn/N}$$

The sequence $s(n)$ can be calculated from $S(k)$ using the IDFT:

$$s(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S(k) e^{j2\pi nk/N}$$

Given the frequency domain sequence STF_freq as specified in 27.1.2.1, the time domain STF can be generated as follows:

$$STF_time = IDFT(STF_freq)$$

The CP with $1/2 T_{STF}$ duration is then prepended to the STF TVWS-NB-OFDM symbol.

27.1.2.3 Time domain STF repetition

There are four repetitions of the STF in the time domain, and the CP with a duration of one-half T_{STF} , as shown in Figure 27-2.

The STF sequence, $STF_time(n)$, is indexed by $n = 0, 1, 2, \dots, N_{ST} - 1$, where N_{ST} is the number of effective subcarriers. $STF_time(n)$ consists of four repetitions of $S(k)$ and can be represented as follows:

$$STF_time(n) = S(MOD(n, N)) \text{ for } n = 0, 1, \dots, 4 \times N - 1$$

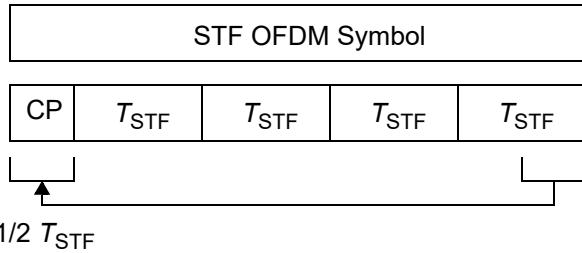


Figure 27-2—STF format for TVWS-NB-OFDM

where

N is 9

$MOD(n, N)$ is the modulo- N operation for any input n

27.1.2.4 STF normalization

The STF uses a fewer number of tones than the PHR field and PHY Payload field, as shown in Figure 27-1. Hence, normalization of the frequency domain STF is required to balance the STF power with that of the rest of the packet. In order to have the same power as the PHR field and PHY Payload field, the normalization value is as follows:

$$\sqrt{\frac{N_{\text{active}}}{N_{\text{STF}}}}$$

where

N_{active} is the number of subcarriers used in the rest of the TVWS-NB-OFDM packet

N_{STF} is the number of subcarriers used in the STF

27.1.3 Long training field (LTF)

27.1.3.1 Frequency domain LTF generation

Table 27-2 shows the frequency domain representation of the LTF.

Table 27-2—Frequency domain representation of LTF for TVWS-NB-OFDM

Tone #	Re	Im	Tone #	Re	Im	Tone #	Re	Im	Tone #	Re	Im
-192	0.051	-0.051	-96	0.051	-0.051	0	0.051	-0.051	96	0.051	-0.051
-191	0	0	-95	0	0	1	0	0	97	0	0
-190	0.0687	-0.0221	-94	0.0221	0.0687	2	-0.0687	0.0221	98	-0.0221	-0.0687
-189	0	0	-93	0	0	3	0	0	99	0	0
-188	0.0319	0.0647	-82	-0.0319	-0.0647	4	0.0319	0.0647	100	-0.0319	-0.0647
-187	0	0	-91	0	0	5	0	0	101	0	0
-186	-0.068	-0.0243	-90	-0.0243	0.068	6	0.068	0.0243	102	0.0243	-0.068

Table 27-2—Frequency domain representation of LTF for TVWS-NB-OFDM (continued)

Tone #	Re	Im									
-185	0	0	-89	0	0	7	0	0	103	0	0
-184	0.0625	0.0361	-88	0.0625	0.0361	8	0.0625	0.0361	104	0.0625	0.0361
-183	0	0	-87	0	0	9	0	0	105	0	0
-182	0.0059	-0.0719	-86	0.0719	0.0059	10	-0.0059	0.0719	106	-0.0719	-0.0059
-181	0	0	-85	0	0	11	0	0	107	0	0
-180	-0.06	-0.0401	-84	0.06	0.0401	12	-0.06	-0.0401	108	0.06	0.0401
-179	0	0	-83	0	0	13	0	0	109	0	0
-178	-0.0642	-0.033	-82	-0.033	0.0642	14	0.0642	0.033	110	0.033	-0.0642
-177	0	0	-81	0	0	15	0	0	111	0	0
-176	-0.0187	-0.0697	-80	-0.0187	-0.0697	16	-0.0187	-0.0697	112	-0.0187	-0.0697
-175	0	0	-79	0	0	17	0	0	113	0	0
-174	0.0721	-0.0035	-78	0.0035	0.0721	18	-0.0721	0.0035	114	-0.0035	-0.0721
-173	0	0	-77	0	0	19	0	0	115	0	0
-172	-0.0647	0.0319	-76	0.0647	-0.0319	20	-0.0647	0.0319	116	0.0647	-0.0319
-171	0	0	-75	0	0	21	0	0	117	0	0
-170	0.0719	0.0059	-74	0.0059	-0.0719	22	-0.0719	-0.0059	118	-0.0059	0.0719
-169	0	0	-73	0	0	23	0	0	119	0	0
-168	0	-0.0722	-72	0	-0.0722	24	0	-0.0722	120	0	-0.0722
-167	0	0	-71	0	0	25	0	0	121	0	0
-166	-0.0467	-0.055	-70	0.055	-0.0467	26	0.0467	0.055	122	-0.055	0.0467
-165	0	0	-69	0	0	27	0	0	123	0	0
-164	-0.0319	-0.0647	-68	0.0319	0.0647	28	-0.0319	-0.0647	124	0.0319	0.0647
-163	0	0	-67	0	0	29	0	0	125	0	0
-162	0.0485	-0.0535	-66	-0.0535	-0.0485	30	-0.0485	0.0535	126	0.0535	0.0485
-161	0	0	-65	0	0	31	0	0	127	0	0
-160	0.0187	0.0697	-64	0.0187	0.0697	32	0.0187	0.0697	128	0.0187	0.0697
-159	0	0	-63	0	0	33	0	0	129	0	0
-158	-0.0221	-0.0687	-62	0.0687	-0.0221	34	0.0221	0.0687	130	-0.0687	0.0221
-157	0	0	-61	0	0	35	0	0	131	0	0
-156	-0.0401	0.06	-60	0.0401	-0.06	36	-0.0401	0.06	132	0.0401	-0.06
-155	0	0	-59	0	0	37	0	0	133	0	0
-154	0.0467	0.055	-58	0.055	-0.0467	38	-0.0467	-0.055	134	-0.055	0.0467
-153	0	0	-57	0	0	39	0	0	135	0	0
-152	0.0625	0.0361	-56	0.0625	0.0361	40	0.0625	0.0361	136	0.0625	0.0361
-151	0	0	-55	0	0	41	0	0	137	0	0

Table 27-2—Frequency domain representation of LTF for TVWS-NB-OFDM (continued)

Tone #	Re	Im									
-150	0.0309	0.0652	-54	-0.0652	0.0309	42	-0.0309	-0.0652	138	-0.0652	0.0309
-149	0	0	-53	0	0	43	0	0	139	0	0
-148	-0.0647	0.0319	-52	0.0647	-0.0319	44	-0.0647	0.0319	140	0.0647	-0.0319
-147	0	0	-51	0	0	45	0	0	141	0	0
-146	0.033	-0.0642	-50	-0.0642	-0.033	46	-0.033	0.0642	142	0.0642	0.033
-145	0	0	-49	0	0	47	0	0	143	0	0
-144	-0.051	0.051	-48	-0.051	0.051	48	-0.051	0.051	144	-0.051	0.051
-143	0	0	-47	0	0	49	0	0	145	0	0
-142	0.0642	0.033	-46	-0.033	0.0642	50	-0.0642	-0.033	146	0.033	-0.0642
-141	0	0	-45	0	0	51	0	0	147	0	0
-140	0.0647	-0.0319	-44	-0.0647	0.0319	52	0.0647	-0.0319	148	-0.0647	0.0319
-139	0	0	-43	0	0	53	0	0	149	0	0
-138	0.0652	-0.0309	-42	-0.0309	-0.0652	54	-0.0652	0.0309	150	0.0309	0.0652
-137	0	0	-41	0	0	55	0	0	151	0	0
-136	0.0625	0.0361	-40	0.0625	0.0361	56	0.0625	0.0361	152	0.0625	0.0361
-135	0	0	-39	0	0	57	0	0	153	0	0
-134	-0.055	0.0467	-38	-0.0467	-0.055	58	0.055	-0.0467	154	0.0467	0.055
-133	0	0	-37	0	0	59	0	0	155	0	0
-132	0.0401	-0.06	-36	-0.0401	0.06	60	0.0401	-0.06	156	-0.0401	0.06
-131	0	0	-35	0	0	61	0	0	157	0	0
-130	-0.0687	0.0221	-34	0.0221	0.0687	62	0.0687	-0.0221	158	-0.0221	-0.0687
-129	0	0	-33	0	0	63	0	0	159	0	0
-128	0.0187	0.0697	-32	0.0187	0.0697	64	0.0187	0.0697	160	0.0187	0.0697
-127	0	0	-31	0	0	65	0	0	161	0	0
-126	0.0535	0.0485	-30	-0.0535	0.0485	66	-0.0535	-0.0485	162	0.0535	-0.0485
-125	0	0	-29	0	0	67	0	0	163	0	0
-124	0.0319	0.0647	-28	-0.0319	-0.0647	68	0.0319	0.0647	164	-0.0319	-0.0647
-123	0	0	-27	0	0	69	0	0	165	0	0
-122	-0.055	0.0467	-26	0.0467	0.055	70	0.055	-0.0467	166	-0.0467	-0.055
-121	0	0	-25	0	0	71	0	0	167	0	0
-120	0	-0.0722	-24	0	-0.0722	72	0	-0.0722	168	0	-0.0722
-119	0	0	-23	0	0	73	0	0	169	0	0
-118	-0.0059	0.0719	-22	-0.0719	-0.0059	74	0.0059	-0.0719	170	0.0719	0.0059
-117	0	0	-21	0	0	75	0	0	171	0	0
-116	0.0647	-0.0319	-20	-0.0647	0.0319	76	0.0647	-0.0319	172	-0.0647	0.0319

Table 27-2—Frequency domain representation of LTF for TVWS-NB-OFDM (continued)

Tone #	Re	Im									
-115	0	0	-19	0	0	77	0	0	173	0	0
-114	-0.0035	-0.0721	-18	-0.0721	0.0035	78	0.0035	0.0721	174	0.0721	-0.0035
-113	0	0	-17	0	0	79	0	0	175	0	0
-112	-0.0187	-0.0697	-16	-0.0187	-0.0697	80	-0.0187	-0.0697	176	-0.0187	-0.0697
-111	0	0	-15	0	0	81	0	0	177	0	0
-110	0.033	-0.0642	-14	0.0642	0.033	82	-0.033	0.0642	178	-0.0642	-0.033
-109	0	0	-13	0	0	83	0	0	179	0	0
-108	0.06	0.0401	-12	-0.06	-0.0401	84	0.06	0.0401	180	-0.06	-0.0401
-107	0	0	-11	0	0	85	0	0	181	0	0
-106	-0.0719	-0.0059	-10	-0.0059	0.0719	86	0.0719	0.0059	182	0.0059	-0.0719
-105	0	0	-9	0	0	87	0	0	183	0	0
-104	0.0625	0.0361	-8	0.0625	0.0361	88	0.0625	0.0361	184	0.0625	0.0361
-103	0	0	-7	0	0	89	0	0	185	0	0
-102	0.0243	-0.068	-6	0.068	0.0243	90	-0.0243	0.068	186	-0.068	-0.0243
-101	0	0	-5	0	0	91	0	0	187	0	0
-100	-0.0319	-0.0647	-4	0.0319	0.0647	92	-0.0319	-0.0647	188	0.0319	0.0647
-99	0	0	-3	0	0	93	0	0	189	0	0
-98	-0.0221	-0.0687	-2	-0.0687	0.0221	94	0.0221	0.0687	190	0.0687	-0.0221
-97	0	0	-1	0	0	95	0	0	191	0	0

27.1.3.2 Time domain LTF generation

The long training field sequence is defined based on a Zadoff Chu sequence with length $N = 192$, a prime number $H = 53$, and $n = 0, 1, \dots, N - 1$. The long training field sequence $l(n)$ in the time domain is expressed as below:

$$(n) = e^{jH\pi n^2/N}, n = 0, 1, 2, \dots, N - 1$$

The DFT of $l(n)$ is defined as $L(k)$, where $k = 0, \dots, N - 1$:

$$L(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} l(n) e^{-j2\pi kn/N}$$

The sequence $l(n)$ can be calculated from $L(k)$ using the IDFT:

$$l(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} L(k) e^{j2\pi nk/N}$$

Given the frequency domain sequence LTF_freq as specified in 27.1.3.1, the time domain LTF is obtained as follows:

$$LTF_time = \text{IDFT}(LTF_freq)$$

The CP with 1/2 LTF duration is then prepended to the LTF TVWS-NB-OFDM symbol.

27.1.3.3 Time domain LTF repetition

The LTF in the time domain shall be formatted as illustrated in Figure 26-3.

The LTF sequence, $LTF_time(n)$, is indexed by $n = 0, 1, 2, \dots, N_{ST} - 1$, where N_{ST} is the number of effective subcarriers. $LTF_time(n)$ is the two repetitions of $L(k)$ and can be represented as follows:

$$LTF_time(n) = L(MOD(n, N)) \text{ for } n = 0, 1, \dots, 2 \times N - 1$$

where

$$\begin{aligned} N &\text{ is } 192 \\ MOD(n, N) &\text{ is the modulo-}N \text{ operation for any input } n \end{aligned}$$

27.1.3.4 LTF normalization

The LTF uses a fewer number of tones than the PHR and PHY payload as shown in Figure 27-1. Hence, normalization of the frequency domain LTF is required to balance the LTF power with that of the rest of the packet. In order to have the same power as the PHR and PHY payload, the normalization value is as follows:

$$\sqrt{\frac{N_{\text{active}}}{N_{\text{LTF}}}}$$

where

$$\begin{aligned} N_{\text{active}} &\text{ is } 384, \text{ the number of subcarriers used in the rest of the TVWS-NB-OFDM packet} \\ N_{\text{LTF}} &\text{ is the number of subcarriers used in the LTF} \end{aligned}$$

27.1.4 PHR

Figure 27-3 shows the PHR format for the TVWS-NB-OFDM PHY.

Bits: 0	1	2–5	6–16	17–20	21–29	30–37	38–43
Reserved	Ranging	Rate	Frame Length	Channel Aggregation	Scrambler Seed	HCS	Tail

Figure 27-3—PHY header fields for TVWS-NB-OFDM

The Ranging field is set to one to indicate that this particular frame is intended for ranging. If the frame is not intended for ranging, the Ranging field is set to zero.

The Rate field specifies the data rate of the payload and is equal to the numerical value of the MCS index as described in 27.3, transmitted MSB first. The data rates for the TVWS-NB-OFDM PHY can be found in 27.3.

The Frame Length field is an unsigned integer that shall be set to the total number of octets in the PSDU (prior to FEC encoding). The Frame Length field shall be transmitted MSB first.

The Channel Aggregation field is used for channel aggregation as described in 27.4. The total number of subchannels used for channel aggregation equals the value of the Channel Aggregation field plus one. If channel aggregation is not used, the Channel Aggregation field is set to zero. The Channel Aggregation field shall be transmitted MSB first.

The Scrambler Seed field specifies the scrambling seed.

The HCS field is an 8-bit CRC taken over the PHR field. The HCS shall be computed using the first 30 bits of the PHR field using the polynomial $G_8(x) = x^8 + x^2 + x + 1$. The HCS is the remainder resulting from $[x^8(b0x^{29} + b1x^{28} + \dots + b28x + b29)]$ divided (modulo 2) by $G_8(x)$, where $b0x^{29} + b1x^{28} + \dots + b28x + b29$ is the polynomial representing the first 30 bits of the PHR for which the checksum is to be computed. At the transmitter, the initial remainder shall be preset to all zeros. The coefficient of the highest order term shall be transmitted first.

The Tail bit field is set to six continuous zeros for Viterbi decoder flushing.

27.1.5 PHY Payload field

The PHY Payload field carries the data of the encoded PSDU.

27.2 System parameters for TVWS-NB-OFDM

Table 27-3 shows system parameters for TVWS-NB-OFDM.

Table 27-3—System parameters for TVWS-NB-OFDM

Parameter	Value
Nominal bandwidth (kHz)	380.95
Subcarrier spacing (kHz)	0.99206 (=125/126)
Total Number of subcarriers – N_{ST}	384
Number of pilot subcarriers per TVWS-NB-OFDM symbol – N_{SP}	32
Number of data subcarriers per TVWS-NB-OFDM symbol – N_{SD}	352
Effective symbol period – T_{FFT} (μs)	1008
Cyclic prefix interval duration – T_{CP} (μs)	Mandatory 1/32 (31.5 μs) Optional: 1/16 (63.0 μs), 1/8 (126.0 μs)
T_{SYM} (μs)	Mandatory 1039.5 Optional 1071.0, 1134.0 ($T_{FFT} + T_{CP}$)
STF duration	1 symbol
LTF duration	1 symbol

27.3 Modulation and coding parameters for TVWS-NB-OFDM

27.3.1 General

The modulation and coding schemes with supported data rates for TVWS-NB-OFDM and corresponding MCS-related parameters are shown in the Table 27-4, where CC stands for inner convolutional coding.

Table 27-4—Data rates for TVWS-NB-OFDM

MCS index	Modulation	CC coding rate	Data rate (kb/s)	CC coded bits per subcarrier (N_{BPSC})	CC coded bits per OFDM symbol (N_{CPBS})	RS encoded data bits per OFDM symbol (N_{DBPS})
MCS0	BPSK	1/2	156	1	352	176
MCS1	BPSK	3/4	234	1	352	264
MCS2	QPSK	1/2	312	2	704	352
MCS3	QPSK	3/4	468	2	704	528
MCS4	16-QAM	1/2	624	4	1408	704
MCS5	16-QAM	3/4	936	4	1408	1056
MCS6	64-QAM	1/2	936	6	2112	1056
MCS7	64-QAM	3/4	1404	6	2112	1584
MCS8	64-QAM	7/8	1638	6	2112	1848

27.3.2 Reference modulator

The reference modulator is illustrated in Figure 27-4.

27.3.3 Scrambler and scrambler seed

The input to the scrambler is the data bits followed by tail bits and then pad bits. The scrambler uses a PN9 sequence that is generated by the generator shown in Figure 17-2. The PN9 scrambler is initialized by the scrambling seed specified by 9 bits in the PHR. The leftmost value of the scrambling seed is placed into the leftmost delay element in Figure 17-2. The PN9 generator is clocked using the seed as the starting point and enabled after the first clock cycle.

27.3.4 Outer encoding

Reed Solomon (RS) encoding (204, 188) shall be used for the outer encoder. The RS encoding is applied with an RS (255, 239) coder as a shortened code. To generate the shortened code, 51 bytes of zeros shall be prepended to each 188-byte input data before RS (255,239) encoding, and the first 51 bytes of zeros shall be removed after the encoding. A root of the primitive polynomial for the RS encoder is as follows:

$$p(x) = 1 + x^2 + x^3 + x^4 + x^8$$

The polynomial generator $g(x)$ shall be the following equation:

$$G(x) = (x - \lambda^0)(x - \lambda^1)(x - \lambda^2)(x - \lambda^3)\dots(x - \lambda^{15})$$

where λ is 0x02.

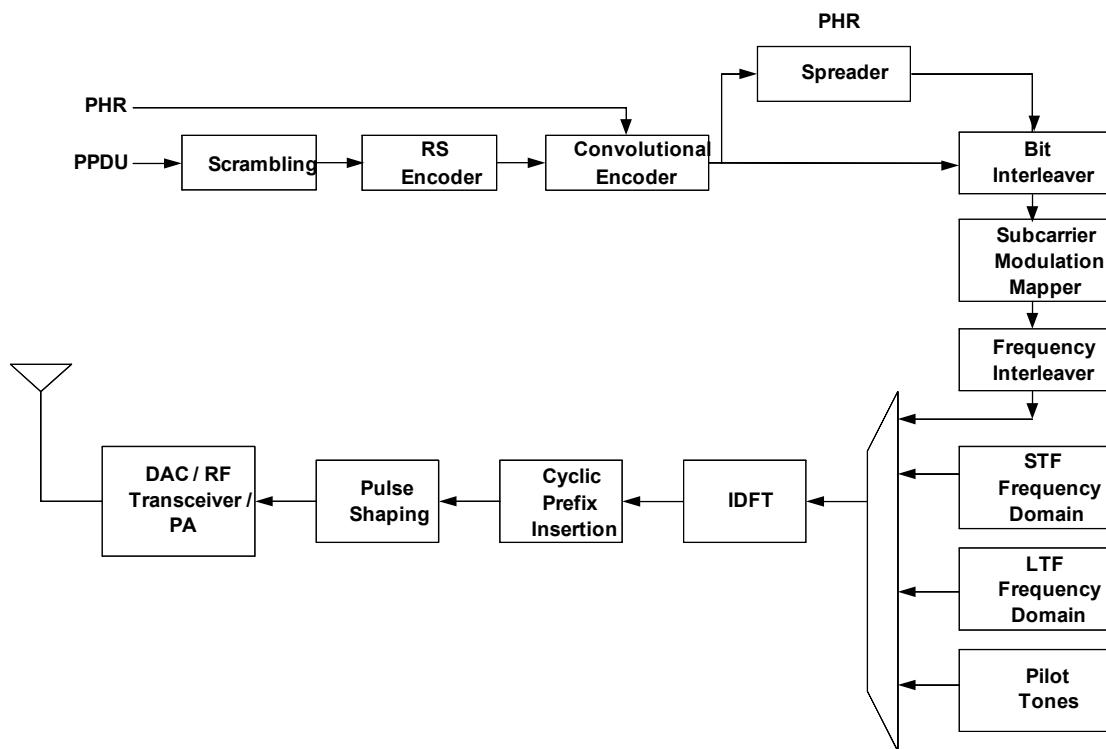


Figure 27-4—Reference modulator diagram for TVWS-NB-OFDM

27.3.5 Inner encoding

A recursive and systematic convolutional encoder of coding rate $R = 1/2, 3/4$, or $7/8$ encodes the RS encoded data bits, 6 tail bits, and pad bits. The convolutional encoder shall use the generator polynomials $g_0 = 171$ and $g_1 = 133$, of rate $R = 1/2$, with feedback connection of g_0 as shown in Figure 27-5.

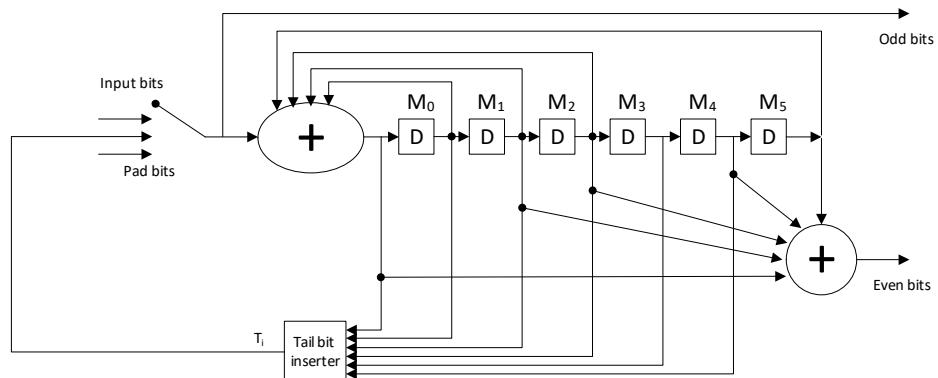


Figure 27-5—Recursive and systematic convolution encoder for TVWS-NB-OFDM

The value of the tail bits are dependent on the memory state shown in Figure 27-5 and shall be set as shown in Table 27-5.

Table 27-5—Tail bit pattern for the recursive and systematic encoder for TVWS-NB-OFDM

Memory state (M0–M5)	Tail bits (T0–T5)						
000000	000000	010000	110010	100000	111001	110000	001011
000001	100001	010001	010010	100001	011001	110001	101011
000010	010000	010010	100010	100010	101001	110010	011011
000011	110000	010011	000010	100011	001001	110011	111011
000100	001000	010100	111010	100100	110001	110100	000011
000101	101000	010101	011010	100101	010001	110101	100011
000110	011000	010110	101010	100110	100001	110110	010011
000111	111000	010111	001010	100111	000001	110111	110011
001000	100100	011000	010110	101000	011101	111000	101111
001001	000100	011001	110110	101001	111101	111001	001111
001010	110100	011010	000110	101010	001101	111010	111111
001011	010100	011011	100110	101011	101101	111011	011111
001100	101100	011100	01111=	101100	010101	111100	100111
001101	001100	011101	111110	101101	110101	111101	000111
001110	111100	011110	001110	101110	000101	111110	110111
001111	011100	011111	101110	101111	100101	111111	010111

Puncturing enables a higher data rate by omitting some of the encoded bits in the transmitter (thus reducing the number of transmitted bits and increasing the coding rate) and inserting a dummy zero metric into the convolutional decoder at the receive side in place of the omitted bits. The puncturing patterns are illustrated in Figure 27-6, Figure 27-7, and Figure 27-8 for the rates 2/3, 3/4, and 7/8, respectively.

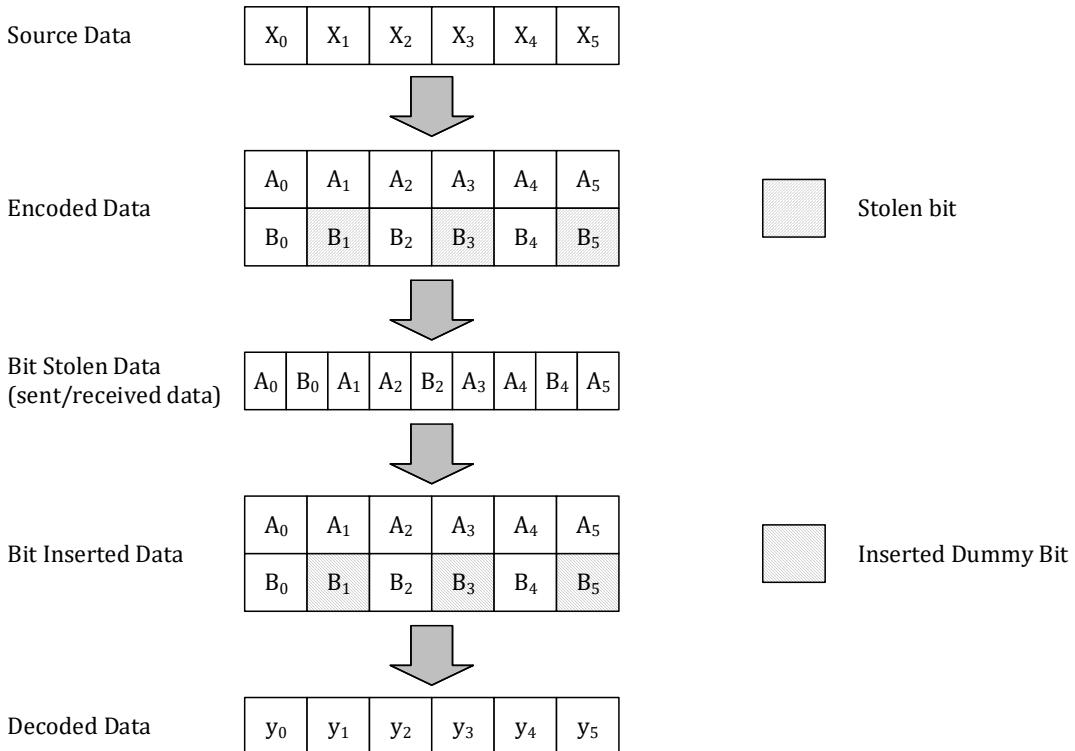


Figure 27-6—R = 2/3 puncturing pattern for TVWS-NB-OFDM

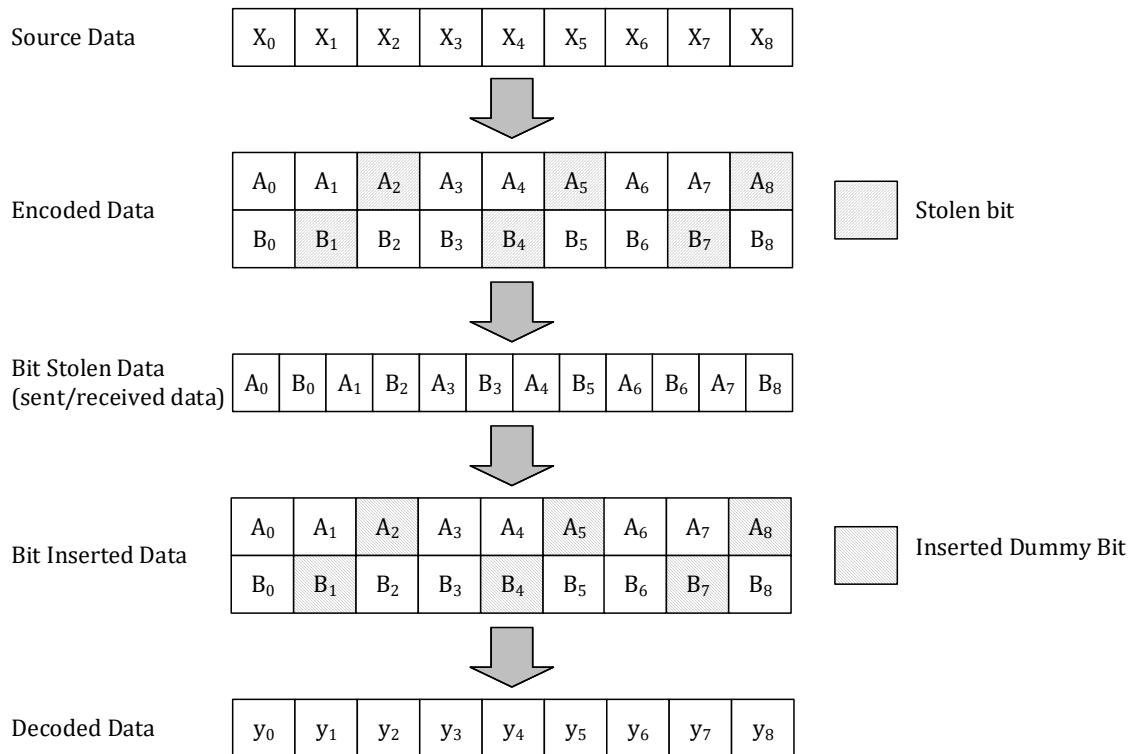


Figure 27-7—R = 3/4 puncturing pattern for TVWS-NB-OFDM

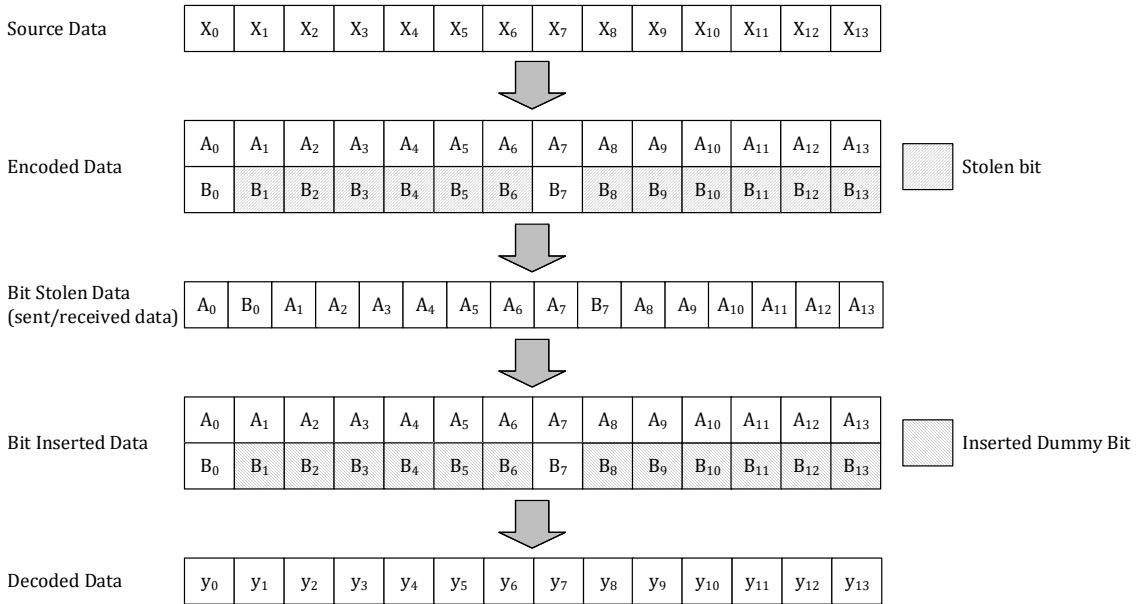


Figure 27-8—R = 7/8 puncturing pattern for TVWS-NB-OFDM

27.3.6 Pad bit insertion

The number of pad bits input to the convolutional encoder, N_{PAD} , shall be computed with the following equations:

$$N_{\text{RS}} = \text{ceiling}(L_{\text{PSDU}} / (188 \times 8))$$

$$L_{\text{RS}} = L_{\text{PSDU}} + N_{\text{RS}} \times 16 \times 8$$

$$N_{\text{SYS}} = \text{ceiling}((L_{\text{RS}} + 6) / N_{\text{DBPS}})$$

$$N_{\text{DATA}} = N_{\text{SYS}} \times N_{\text{DBPS}}$$

$$N_{\text{PAD}} = N_{\text{DATA}} - (x L_{\text{RS}} + 6)$$

L_{PSDU} is the number of PSDU bits, which is equal to the content of the Frame Length field in Figure 27-3, and N_{DBPS} is shown in Table 27-4.

The function ceiling() returns the smallest integer value greater than or equal to its argument value. The pad bits are set to zeros.

27.3.7 Spreader

The spreader only applies to the PHR field. The PHR field is encoded using the rate 1/2 recursive convolutional code as described in 27.3.5 to create an 88-bit sequence ($d_0, d_1, d_2, \dots, d_{87}$). The 88-bit sequence is spread by using a spreading sequence [1111] to generate the 352-bit sequence ($d_0, d_0, d_0, d_0, d_1, d_1, d_1, d_1, d_2, d_2, d_2, d_2, \dots, d_{87}, d_{87}, d_{87}, d_{87}$). The 352-bit sequence is then interleaved as described in 27.3.8 and mapped using BPSK as described in 27.3.9. The resulting values are interleaved in the frequency domain as described in 27.3.10; pilots are inserted as described in 27.3.11 and then modulated as a TVWS-NB-OFDM symbol.

27.3.8 Bit interleaving

All encoded data bits shall be interleaved by a block interleaver with a block size corresponding to the number of encoded bits in a single TVWS-NB-OFDM symbol, N_{CBPS} . The interleaver is defined by a two-step permutation.

The first permutation is defined by the following rule:

$$i = (N_{\text{CBPS}} / 44) (k \bmod 44) + \text{floor}(k / 44), k = 0, 1, \dots, N_{\text{CBPS}} - 1$$

Here, k shall be the index of the coded bit before the first permutation; and i shall be the index after the first and before the second permutation. The function $\text{floor}()$ denotes the largest integer not exceeding the parameter. The second permutation is defined by the following rule:

$$j = s \times \text{floor}(i / s) + (i + N_{\text{CBPS}} - \text{floor}(44 \times i / N_{\text{CBPS}})) \bmod s, i = 0, 1, \dots, N_{\text{CBPS}} - 1$$

where j is the index after the second permutation, just prior to mapping. The value of s is determined by the number of coded bits per subcarrier, N_{BPSC} , as follows:

$$s = \max(N_{\text{BPSC}} / 2, 1)$$

where N_{BPSC} is shown in Table 27-4. The deinterleaver, which performs the inverse relation, is also defined by these two corresponding permutations.

27.3.9 Subcarrier mapping

The TVWS-NB-OFDM subcarriers shall be modulated by using BPSK, QPSK, 16-QAM, or 64-QAM modulation. The encoded and interleaved binary serial input data shall be parsed into N_{BPSC} bits per symbol and mapped onto I- and Q-channel data. The conversion shall be performed according to Gray-coded constellation mapping, illustrated in Figure 27-9, with the input bit, b_0 , being the earliest in the stream.

The output values, d , are formed by multiplying the resulting $(I + jQ)$ values by a normalization factor K_{MOD} , as described in the following equation:

$$d = (I + jQ) \times K_{\text{MOD}}$$

The normalization factor, K_{MOD} , depends on the base modulation mode, as prescribed in Table 27-6.

Table 27-6—Modulation-dependent normalization factor K_{MOD} for TVWS-NB-OFDM

Modulation	K_{MOD}
BPSK	1
QPSK	$1/\sqrt{2}$
16-QAM	$1/\sqrt{10}$
64-QAM	$1/\sqrt{42}$

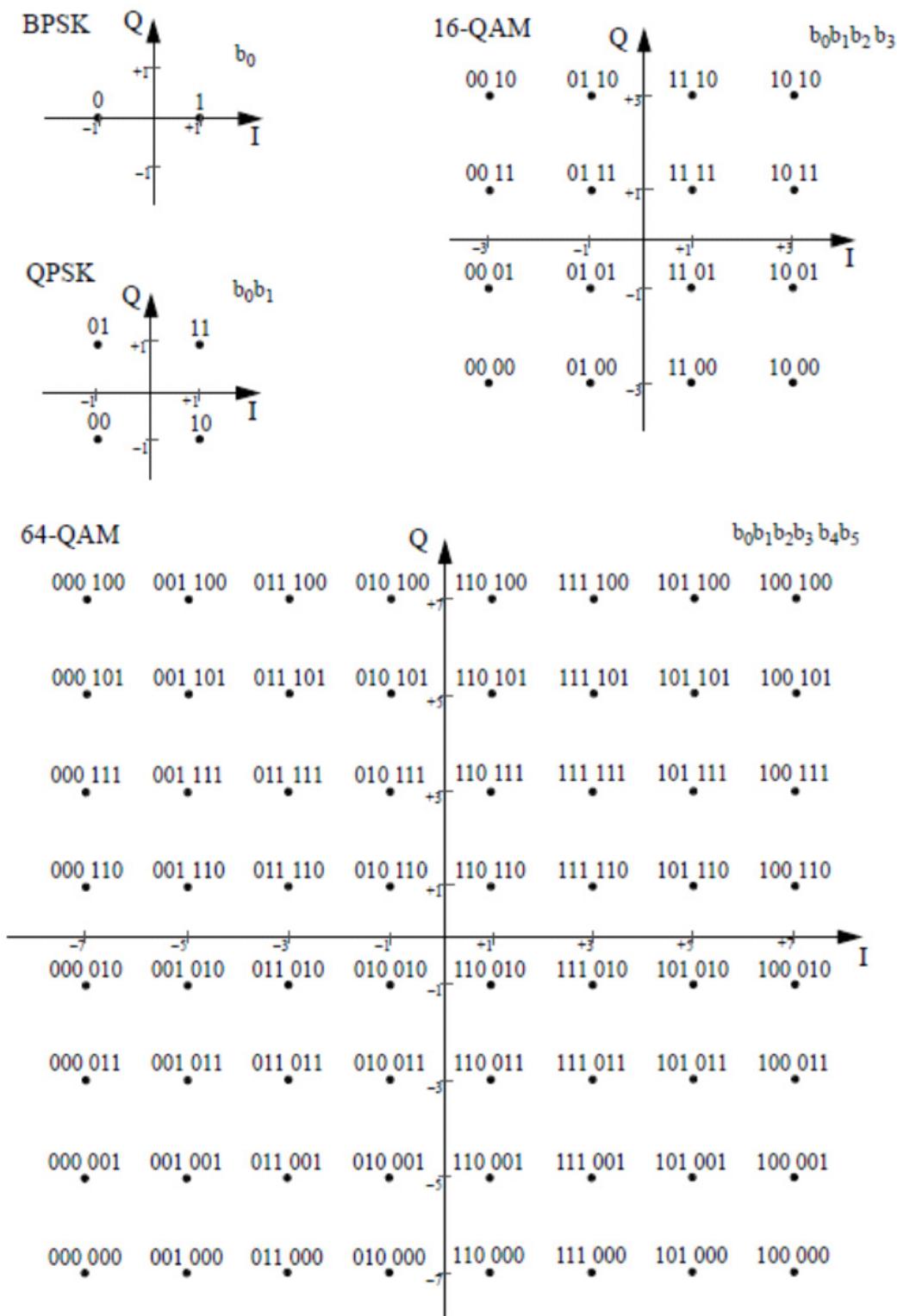


Figure 27-9—Constellation mapping for TVWS-NB-OFDM

27.3.10 Frequency interleaving

A random interleaver is used for frequency interleaving. The permutation rule for the frequency interleaving is specified as follows.

The index of an input bit before interleaving is represented by i ; J , the index of an output bit after interleaving shall be represented as follows:

$$J=Z(i) \text{ for } i = 0, 1, \dots, 352-1$$

where $Z=[63\ 14\ 12\ 286\ 337\ 221\ 227\ 93\ 57\ 47\ 121\ 176\ 299\ 173\ 236\ 54\ 165\ 188\ 126\ 83\ 6\ 46\ 174\ 259\ 136\ 183\ 142\ 274\ 127\ 265\ 287\ 89\ 234\ 62\ 250\ 311\ 180\ 156\ 58\ 124\ 209\ 15\ 228\ 101\ 312\ 206\ 80\ 185\ 186\ 329\ 78\ 116\ 278\ 113\ 21\ 200\ 179\ 144\ 153\ 216\ 205\ 140\ 235\ 193\ 310\ 184\ 82\ 130\ 257\ 315\ 102\ 44\ 98\ 325\ 143\ 158\ 91\ 215\ 103\ 30\ 304\ 262\ 32\ 23\ 53\ 306\ 302\ 294\ 178\ 117\ 297\ 86\ 197\ 192\ 115\ 59\ 199\ 17\ 168\ 146\ 120\ 246\ 114\ 296\ 194\ 233\ 18\ 109\ 284\ 247\ 65\ 238\ 190\ 129\ 303\ 321\ 240\ 336\ 40\ 348\ 352\ 74\ 159\ 277\ 244\ 100\ 39\ 288\ 4\ 331\ 154\ 316\ 118\ 290\ 214\ 211\ 150\ 338\ 340\ 152\ 242\ 322\ 218\ 31\ 335\ 162\ 323\ 50\ 177\ 13\ 347\ 61\ 29\ 230\ 266\ 289\ 226\ 60\ 182\ 171\ 320\ 342\ 87\ 252\ 134\ 345\ 110\ 45\ 269\ 258\ 324\ 56\ 318\ 122\ 261\ 276\ 191\ 20\ 64\ 19\ 249\ 10\ 241\ 212\ 151\ 231\ 333\ 232\ 72\ 256\ 351\ 84\ 88\ 155\ 219\ 139\ 270\ 349\ 131\ 161\ 279\ 217\ 237\ 309\ 224\ 255\ 26\ 99\ 301\ 202\ 138\ 220\ 37\ 326\ 125\ 67\ 170\ 22\ 36\ 108\ 51\ 107\ 334\ 327\ 263\ 253\ 272\ 264\ 137\ 1\ 207\ 160\ 123\ 189\ 7\ 285\ 97\ 27\ 201\ 198\ 187\ 346\ 341\ 350\ 104\ 85\ 229\ 213\ 3\ 68\ 319\ 2\ 75\ 343\ 167\ 195\ 34\ 69\ 268\ 112\ 119\ 141\ 196\ 106\ 203\ 292\ 260\ 24\ 172\ 66\ 282\ 25\ 166\ 9\ 95\ 223\ 332\ 35\ 239\ 267\ 90\ 81\ 254\ 164\ 281\ 248\ 5\ 291\ 280\ 55\ 79\ 181\ 73\ 317\ 283\ 132\ 208\ 344\ 307\ 222\ 133\ 8\ 149\ 300\ 169\ 225\ 49\ 48\ 314\ 76\ 105\ 71\ 148\ 41\ 111\ 70\ 147\ 38\ 175\ 42\ 33\ 305\ 308\ 313\ 16\ 273\ 135\ 243\ 204\ 210\ 163\ 298\ 328\ 11\ 94\ 43\ 251\ 157\ 339\ 293\ 145\ 295\ 330\ 128\ 271\ 77\ 96\ 92\ 245\ 275\ 28\ 52].$

Figure 27-10 shows the distribution of interleaving for input bits before interleaving versus output bits after interleaving.

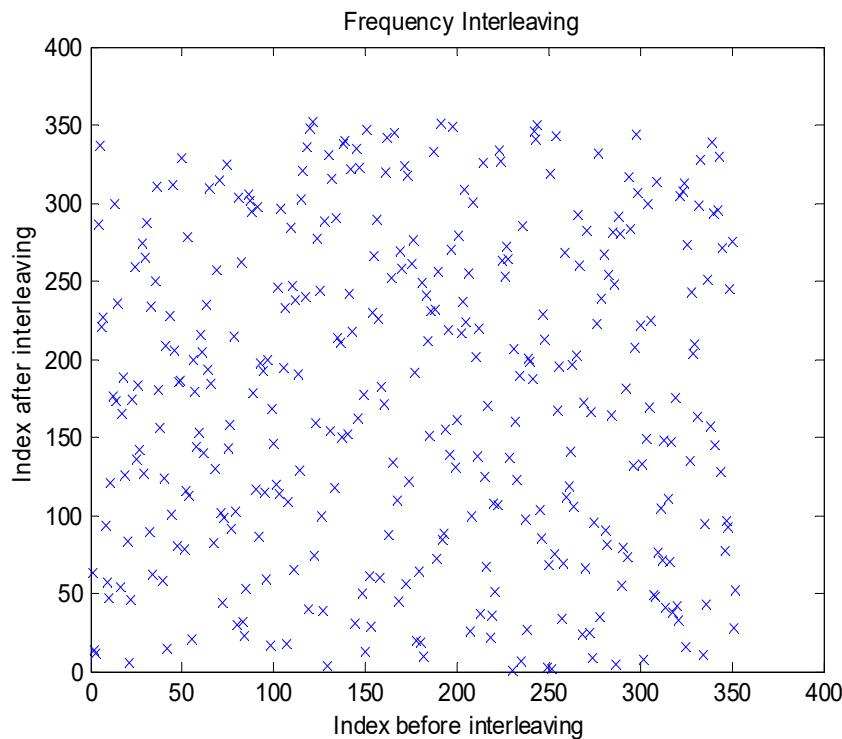


Figure 27-10—Illustration of frequency interleaving mapping for TVWS-NB-OFDM

27.3.11 Pilot tones

Figure 27-11 shows the pilot symbol pattern of TVWS-NB-OFDM. As shown in the figure, the pilot symbol is inserted into a frame once every 12 subcarriers in the frequency direction and once every 4 symbols in the symbol or time direction.

		Frequency																		
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	383
Time	0	Pilot												Pilot			
	1			Pilot													
	2							Pilot									
	3										Pilot						
	4	Pilot													Pilot		
	
	
	
	
	200	Pilot												Pilot			
	201			Pilot													
	202							Pilot									
	203										Pilot						

Figure 27-11—Pattern of pilot subcarriers allocated in TVWS-NB-OFDM symbol

27.3.12 Cyclic prefix

A cyclic prefix shall be prepended to each TVWS-NB-OFDM symbol. For the STF, the CP is defined in 27.1.2.3. For the LTF, the CP is defined in 27.1.3.3. For the rest of the TVWS-NB-OFDM symbols the duration of the cyclic prefix (31.5 µs) shall be 1/32 of the base TVWS-NB-OFDM symbol (1008 µs). Optionally, the cyclic prefix of duration 63 µs, which is 1/16 of the base TVWS-NB-OFDM symbol, or the cyclic prefix of duration 126 µs, which is 1/8 of the base TVWS-NB-OFDM symbol, can be selected.

27.3.13 Pulse shaping

Time domain windowing shall be applied during TVWS-NB-OFDM signal generation in order to smooth the transition between two consecutive TVWS-NB-OFDM symbols. This can reduce spectral leakage for both cases when combined with and without implementing any digital pulse shaping filter in TVWS-NB-OFDM. When time domain windowing is applied for pulse shaping, a windowing function $w(t)$, as exemplified in the following equation, shall be utilized after insertion of cyclic prefix.

$$w(t) = \begin{cases} \sin^2\left(\frac{\pi}{2}(0.5 + t/T_{TR})\right) & -T_{TR}/2 < t < T_{TR}/2 \\ 1 & T_{TR}/2 \leq t < T - T_{TR}/2 \\ \sin^2\left(\frac{\pi}{2}(0.5 - (t - T)/T_{TR})\right) & (T - T_{TR})/2 \leq t < T + T_{TR}/2 \end{cases}$$

where T_{TR} , the windowing duration, is the duration of the transition from the minimum to maximum value of the windowing function and vice versa.

The continuous pulse shaped waveform is expressed as follows:

$$s(t) = w(t) \frac{1}{\sqrt{N_{ST}}} \sum_{n=0}^{N_{ST}-1} S_n e^{j2\pi n \Delta f(t - T_{CP})}$$

The parameters Δf , which denotes sub-carrier spacing, and N_{ST} are described in Table 27-3. S_n is defined as data, pilot, or training symbols. The binding requirements are the spectral mask and modulation accuracy requirements.

NOTE—In the receiver, shifting the time by more than T_{CP} for application of DFT helps to avoid intersymbol interference caused by the superposition of the extended TVWS-NB-OFDM symbols and inter-carrier interference caused by the windowing.

27.3.14 PIB attribute values for *phySymbolsPerOctet*

The number of symbols per octet depends on the MCS mode applied and is computed as follows:

$$\text{phySymbolsPerOctet} = 8 \times n/k \times 1/N_{\text{dbps}}$$

where

- n is 204
- k is 188

27.4 Channel aggregation for TVWS-NB-OFDM

The use of channel aggregation is controlled by the *phyTvwsChannelAggregation* as described in Table 12-9. When channel aggregation is enabled at least one of the bandwidths, 6 MHz or 8 MHz, shall be supported. The maximum number of aggregated channels depends on the availability of channel bandwidth. Table 27-7 shows the channel aggregation parameters.

Table 27-7—Channel aggregation parameters for TVWS-NB-OFDM

Maximal bandwidth on channel aggregation use	6 MHz	8 MHz
Maximal number of subchannels available for aggregation	11	16
Channel spacing	400.79365 kHz (= 125/126 kHz × 404)	
Guard band for each side of channel	795.63495 kHz	793.6508 kHz

27.5 TVWS-NB-OFDM RF requirements

27.5.1 Operating frequency range

The TVWS-NB-OFDM PHY operates in the bands indicated in Table 10-47.

27.5.2 Receiver sensitivity

The sensitivity requirements, as described in 11.1.8, for each MCS mode are shown in Table 27-8.

Table 27-8—TVWS-NB-OFDM PHY sensitivity requirements

MCS mode	Sensitivity
0	-97 dBm
1	-96 dBm
2	-94 dBm
3	-92 dBm
4	-89 dBm
5	-85 dBm
6	-81 dBm
7	-80 dBm
8	-78 dBm

27.5.3 TX-to-RX turnaround time

The TX-to-RX turnaround time shall be as given in 11.2.2.

27.5.4 RX-to-TX turnaround time

The RX-to-TX turnaround time shall be as given in 11.2.3.

27.5.5 EVM definition

The relative constellation RMS error averaged over subcarriers, symbols, and packets shall not exceed the values shown in Table 27-9.

Table 27-9—TVWS-NB-OFDM PHY EVM requirements

MCS mode	RMS error
0	-3 dB
1	-5 dB
2	-8 dB
3	-11 dB
4	-14 dB
5	-17 dB
6	-20 dB
7	-23 dB
8	-26 dB

The transmit modulation accuracy test shall be performed by instrumentation capable of converting the transmitted signal into a stream of complex samples. The sampled signal shall be processed in a manner similar to an actual receiver, according to the following steps, or an equivalent procedure:

- a) Detect the start of packet.
- b) Detect the transition from STF to LTF, and establish fine timing (with one sample resolution).
- c) Estimate the coarse and fine frequency offsets.
- d) De-rotate the packet according to estimated frequency offset.
- e) Estimate the complex channel response coefficients for each of the subcarriers.
- f) For each data TVWS-NB-OFDM symbol, transform the symbol into subcarrier received values, and divide each subcarrier value with the estimated channel response coefficient.
- g) For each data-carrying subcarrier, find the closest constellation point, and compute the squared Euclidean distance from it.
- h) Compute the RMS average of all errors in a packet:

$$RMS_{\text{error}} = 20\log_{10} \left(\frac{1}{N_F} \sum_{i=1}^{N_F} \sqrt{\frac{\sum_{j=1}^{N_{\text{SYM}}} \sum_{k \in U_D} \Delta(i, j, k)^2}{352 \times N_{\text{SYM}} \times P_0}} \right)$$

with

$$\Delta(i, j, k)^2 = [I(i, j, k) - I_0(i, j, k)]^2 + [Q(i, j, k) - Q_0(i, j, k)]^2$$

where

N_{SYM}	is the number of TVWS-NB-OFDM symbols in the packet
N_F	is the number of packets used for the measurement
U_D	is the index set of data tones
$[I_0((i,j,k),Q_0(i,j,k))]$	denotes the ideal symbol point of the i th packet, j th TVWS-NB-OFDM symbol of the packet, and k th subcarrier of the TVWS-NB-OFDM symbol in the complex plane
$[I((i,j,k),Q(i,j,k))]$	denotes the observed point of the i th packet, j th TVWS-NB-OFDM symbol of the packet, and k th tone of the TVWS-NB-OFDM symbol in the complex plane
P_0	is the average power of the constellation

The test shall be performed over at least $N_F = 20$ packets. The payload of the packets under test shall contain $N_{\text{SYM}} = 16$ TVWS-NB-OFDM symbols. Random data shall be used for the payload.

27.5.6 Transmit center frequency and symbol tolerance

The transmit center frequency tolerance shall be $\pm 20 \times 10^{-6}$ maximum. The symbol clock frequency tolerance shall also be $\pm 20 \times 10^{-6}$ maximum. The transmit center frequency and the symbol clock frequency shall be derived from the same reference oscillator.

28. RCC LMR PHY

28.1 RCC PHY overview

The RCC LMR PHY is specified for use in RCC applications. An RCC device shall support the LMR PHY with GMSK modulation and a data rate of 9.6 kb/s. For the purposes of calculating the Ack frame timing required in 6.6.4, the parameters for an RCC LMR PHY with GMSK modulation and a data rate of 9.6 kb/s shall be used.

28.2 PPDU format

28.2.1 General

The LMR PHY PPDU shall be formatted as illustrated in Figure 28-1.

Bits: 32/64	4	11	8	0/6	variable	0/6	variable	0/3
	Data FEC Type	Data Length	CRC	PHR FEC Tail	PSDU	Payload FEC Tail	Pad	
SHR	PHR				PHY payload			Tail

Figure 28-1—Format of the RCC PPDU

28.2.2 SHR

The SHR shall be selected from the values shown in Table 28-1.

Table 28-1—SHR values for RCC LMR PHY

Modulation	SHR value for FEC coded PHR	SHR value for FEC uncoded PHR
GMSK 9.6/19.2 kb/s	1111 1000 0011 1000 1001 0000 1110 1101	0000 0111 1100 0111 0110 1111 0001 0010
4-FSK 9.6/19.2/38.4 kb/s	0101 0101 0111 1111 1111 01 0101 1111 1101 1111 0111 11 1111 0101 0111 0101 1101	1111 1111 1101 0101 0101 11 1111 0101 0111 0101 1101 01 0101 1111 1101 1111 0111
QPSK 16/32 kb/s	1100 1100 1100 1100 1100 11 1111 0000 0011 0000 1100 00 0000 1111 1100 1111 0011	1100 1100 1100 1100 1100 11 1111 0000 0011 0000 1100 11 1111 0000 0011 0000 1100
$\pi/4$ DQPSK 16/32/36 kb/s	0101 0101 0111 1111 1111 01 0101 1111 1101 1111 0111 11 1111 0101 0111 0101 1101	1111 1111 1101 0101 0101 11 1111 0101 0111 0101 1101 01 0101 1111 1101 1111 0111
DSSS DBPSK	1010 1010 1011 1000 1001 0000 1110 1101	10 1010 1011 1000 1001 0111 0001 0010
DSSS DQPSK	1100 1100 1100 1100 1100 11 1111 0000 0011 0000 1100 00 0000 1111 1100 1111 0011	1100 1100 1100 1100 1100 11 1111 0000 0011 0000 1100 11 1111 0000 0011 0000 1100

28.2.3 PHR

The Data FEC Type field indicates the encoding of the PSDU. The field shall have one of the non-reserved values given in Table 28-2, and shall be set according to the value of *phyLmrCodingRate*. See 28.3 for more information on coding.

Table 28-2—Data FEC Type field for RCC LMR PHY

Data FEC Type field value	Coding rate
0000	1 (no FEC)
0001	7/8
0010	3/4
0011	2/3
0100	1/2
0101–1111	Reserved

The Data Length field is an unsigned integer and shall be set to the total number of octets contained in the PSDU. The Data Length field shall be transmitted MSB first.

The Data FEC Type and Data Length fields shall be protected with an 8-bit CRC. The polynomial and the details of its calculation are given in 20.2.3. The protected bits shall be processed in transmit order, and the CRC field shall be transmitted with the highest term first. All CRC calculations shall be made prior to data whitening.

When FEC is applied to the PHR, the PHR FEC Tail field shall have a length of 6 bits (i.e., six FEC tail bits are appended after the CRC field to aid in FEC decoding). When the PHY header is not FEC protected, the PHR FEC Tail field shall have length zero (i.e., no tail bits are appended).

28.2.4 PHY payload

The Payload FEC Tail field shall be present only if the PSDU is FEC protected, as indicated by the Data FEC Type field.

The length of the Pad field depends on the selected coding rate. The total number of bits contained in the PSDU, Payload FEC Tail, and Pad fields shall be an integer multiple of the interleaver block size.

28.2.5 Tail bits

Three extra zero bits shall be appended at the end of the packet if GMSK modulation is used.

28.3 FEC

FEC protection of the PHR shall be supported. When FEC is enabled, the rate $\frac{1}{2}$ code shall be used.

FEC protection of the PHY payload shall be supported. The PSDU shall be coded using one of the values contained in Table 28-2, corresponding to the desired data rate. The convolutional encoder shall use generator polynomials $g_0 = 133_8$ and $g_1 = 171_8$ for rate $\frac{1}{2}$, as shown in Figure 28-2. Higher rates are achieved by puncturing, according to Figure 28-3.

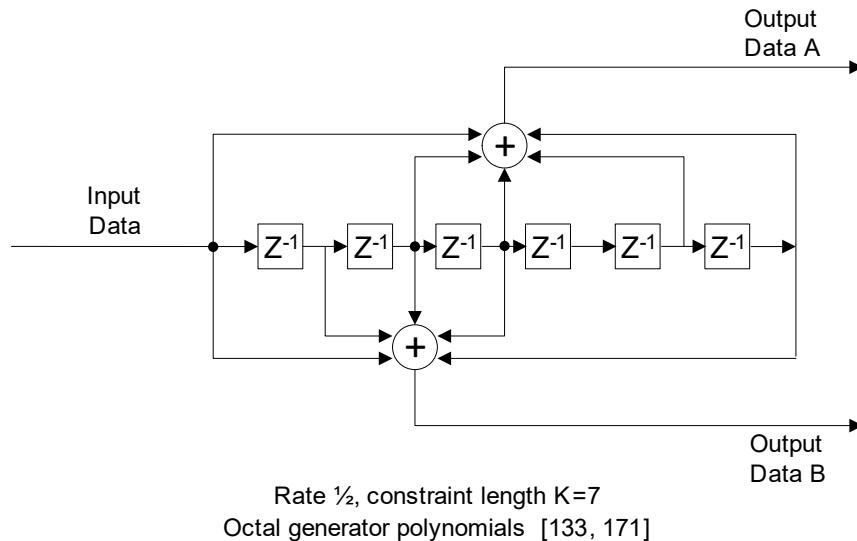


Figure 28-2—Convolutional encoder for RCC LMR PHY

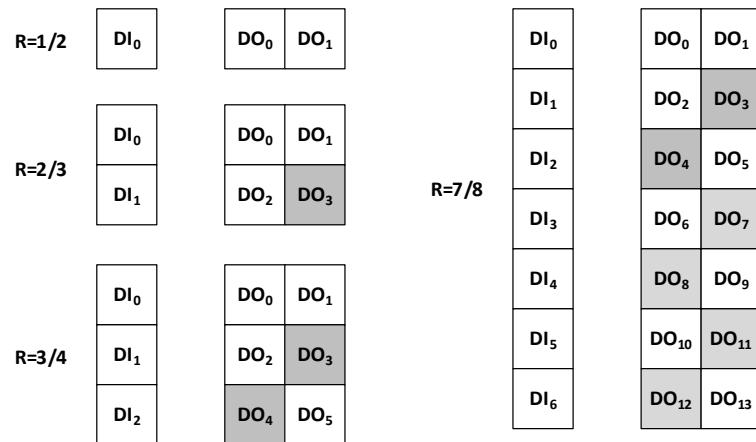


Figure 28-3—FEC puncturing pattern for RCC LMR PHY

28.4 Interleaver

Interleaving of the PHY payload shall be supported. Interleaving shall be enabled when FEC is enabled. Interleaving shall be disabled when FEC is disabled.

The process of interleaving is illustrated in Figure 28-4.

28.5 Data whitening

Support for data whitening is optional. Data whitening shall be applied to the PHR and PHY payload, as described in 17.2.3. The PN9 sequence generator shall not be reset between the PHR and the PSDU.

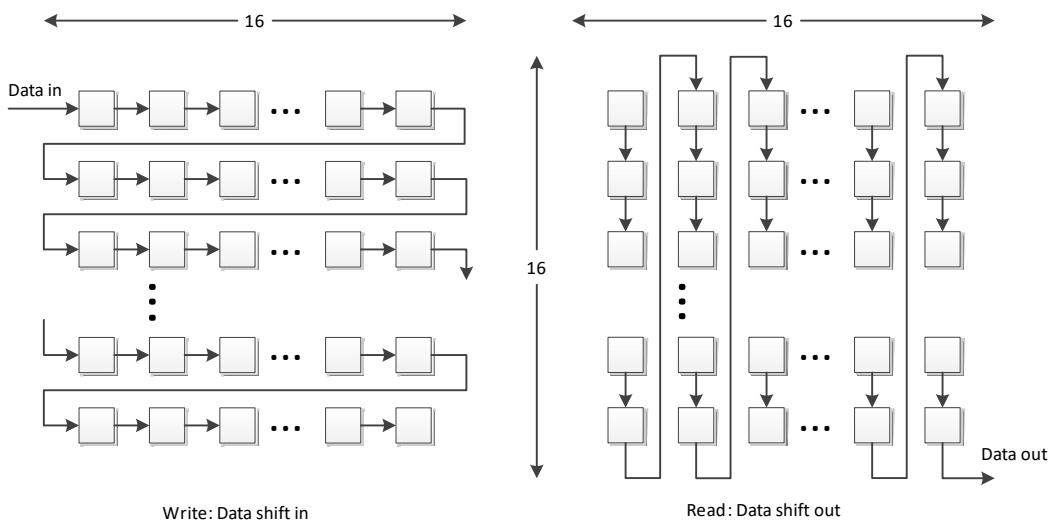


Figure 28-4—Interleaver for RCC LMR PHY

28.6 Modulation

28.6.1 GMSK

The bit sequences are modulated onto the carrier using GMSK, where the Gaussian filter BT is nominally 0.3. A bit value of one is transmitted by shifting the frequency higher than the channel center frequency, and a bit value of zero is transmitted by shifting the frequency lower than the channel center frequency.

The nominal frequency deviation shall be 1/4 of the symbol rate. The deviation shall be between 25% and 130% of the nominal deviation. For the sequence 0101, the deviation shall be between 25% and 110% of the nominal deviation. For the sequence 00001111, the deviation shall be between 80% and 130% of the nominal deviation. The excursions for the zero crossings for all trajectories of the eye diagram shall be constrained to within $\pm 12.5\%$ of the symbol time.

28.6.2 4-FSK

Figure 28-5 shows a typical 4-FSK modulator in a digital implementation.

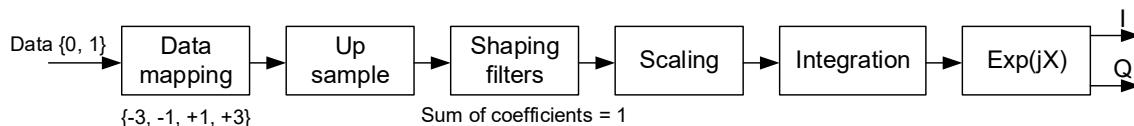


Figure 28-5—Typical 4-FSK modulator for RCC LMR PHY

The shaping filters consists of a Nyquist raised cosine filter cascaded with an inverse-sinc filter. The frequency response of the Nyquist raised cosine filter $H(f)$ is as follows:

$$|H(f)| = 1, \quad \text{for } |f| < \text{symbol rate} \times 0.4$$

$$|H(f)| = 0.5 + 0.5 \cos \left[\frac{2 \times \pi \times f}{\text{symbol rate} \times 0.4} \right], \quad \text{for } (\text{symbol rate} \times 0.4) < |f| < (\text{symbol rate} \times 0.6)$$

$$|H(f)| = 0, \quad \text{for } (|f| > \text{symbol rate} \times 0.6)$$

The amplitude response of the inverse-sinc filter $P(f)$ is as follows:

$$|P(f)| = \begin{cases} \left(\frac{\pi \times f}{\text{symbol rate}} \right), & \text{for } |f| < (\text{symbol rate} \times 0.6) \\ \left(\frac{\sin(\pi \times f)}{\text{symbol rate}} \right), & \text{for } (\text{symbol rate} \times 0.6) < |f| \end{cases}$$

The response of $P(f)$ for $|f| > \text{symbol rate} \times 0.6$ is not specified for frequencies above symbol rate $\times 0.6$, because these frequencies are cut off by $H(f)$.

The data mapping and frequency deviation, f_{dev} , are indicated in Table 20-11. The value of f_{dev} is as follows:

$$f_{\text{dev}} = 3/8 \times \text{symbol rate}$$

The modulation quality is as specified in 20.3.4, with the exception that it is measured after the square root raised cosine filter in the receiver.

28.6.3 QPSK

Figure 28-6 shows a typical QPSK modulator in a digital implementation. This functional block diagram serves as a reference for specifying the LMR PHY with QPSK modulation.

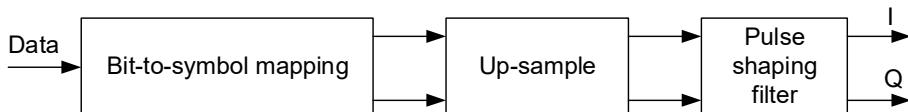


Figure 28-6—Typical QPSK modulator for RCC LMR PHY

The bit-to-symbol mapping shall be encoded according to Table 28-3. The pulse shaping filter shall be equivalent to a root cosine filter with a roll-off factor of 0.25.

Table 28-3—QPSK encoding values for RCC LMR PHY

Data {b1, b0}	Phase
01	$+3/4 \times \pi$
00	$+1/4 \times \pi$
10	$-1/4 \times \pi$
11	$-3/4 \times \pi$

28.6.4 $\pi/4$ DQPSK

Figure 28-7 shows a typical $\pi/4$ DQPSK modulator in a digital implementation. This functional block diagram is provided as a reference for specifying the LMR PHY using $\pi/4$ DQPSK modulation.

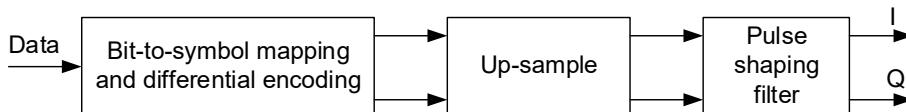


Figure 28-7—Typical $\pi/4$ DQPSK modulator for RCC LMR PHY

The bit-to-symbol mapping and differential encoding shall be encoded according to Table 28-4. The pulse shaping filter shall be a root raised cosine filter with a roll-off factor of 0.25.

Table 28-4— $\pi/4$ DQPSK encoding values for RCC LMR PHY

Data (b1 b0)	Phase change
01	$+3/4 \times \pi$
00	$+1/4 \times \pi$
10	$-1/4 \times \pi$
11	$-3/4 \times \pi$

28.6.5 DSSS DPSK

The modulation for DSSS DPSK is either DSSS DBPSK or DSSS DQPSK.

The functional block diagram shown in Figure 28-8 is provided as a reference for specifying the DSSS DPSK modulation and spreading functions.



Figure 28-8—DSSS DPSK modulation and spreading

The bit-to-symbol mapping and differential encoding for DSSS DBPSK shall be encoded according to Table 28-5.

Table 28-5—DSSS DBPSK encoding

Data	Phase change
0	0
1	π

The bit-to-symbol mapping and differential encoding for DSSS DQPSK shall be encoded according to Table 28-6.

Table 28-6—DSSS DQPSK encoding

Bits (d_0, d_1) ^a	Phase change
00	0
01	$\pi/2$
11	π
10	$-\pi/2$

^a Bit d_0 is transmitted first in time.

The spreading sequences are specified in Table 28-7. The leftmost chip shall be transmitted first in time.

Table 28-7—DSSS DPSK spreading sequences

Spreading sequence length	Spreading sequence
11	111 0001 0010
15	101 1111 0100 0110
20	1010 1000 0011 0110 0111
40	1010 0011 1001 0010 1101 1101 1001 1010 1011 1111

The chip rates are specified in Table 28-8.

Table 28-8—DSSS DPSK chip rates

DSSS DPSK chip rates
300 kcps
600 kcps
800 kcps
1 Mcps
1.6 Mcps

Table 28-8—DSSS DPSK chip rates (continued)

DSSS DPSK chip rates
2 Mcps
3 Mcps
4 Mcps

28.7 Reference modulator

The functional block diagram in Figure 28-9 serves as a reference for specifying the LMR PHY data flow processing functions. Data whitening shall be applied over the PHR and PHY payload continuously. The six FEC tail bits shall be replaced by six non-scrambled zeros prior to FEC encoding. When FEC is enabled, FEC processing for the PHR and PHY payload shall be performed separately.

All fields in the PPDU shall use the same symbol rate and modulation.

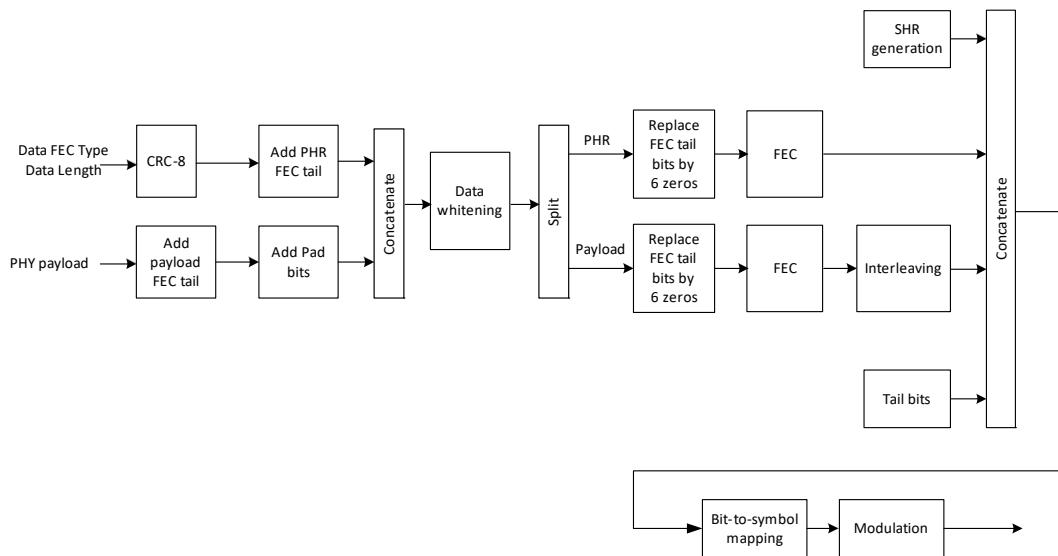


Figure 28-9—RCC LMR PHY reference modulator diagram

28.8 LMR PHY RF requirements

28.8.1 Transmitter symbol rate tolerance

The transmitter symbol rate error shall be less than or equal to $\pm 5 \times 10^{-6}$.

28.8.2 Channel switching time

The channel switching time shall be less than or equal to 500 μ s.

28.8.3 Error vector magnitude

When the LMR PHY is using either QPSK or $\pi/4$ DQPSK modulation, it shall have EVM values of less than 35% when measured for 1000 symbols using the measurement process defined in 11.2.4.

28.8.4 Receiver sensitivity

Receiver sensitivity is implementation specific; however, the method for measuring receiver sensitivity is described in 11.1.8.

28.8.5 Receiver interference rejection

The minimum receiver interference rejection is implementation specific.

28.8.6 Receiver maximum input level of desired signal

The receiver maximum input level is implementation specific.

28.8.7 TX-to-RX turnaround time

The TX-to-RX turnaround time shall be less than or equal to 5 symbols.

28.8.8 RX-to-TX turnaround time

The RX-to-TX turnaround time shall be less than or equal to 5 symbols.

28.8.9 Receiver ED

The LMR PHY shall provide the receiver ED measurement, as described in 11.2.6.

28.8.10 LQI

The LMR PHY shall provide the LQI measurement, as described in 11.2.7.

29. RCC DSSS BPSK PHY

29.1 Overview

The RCC DSSS BPSK PHY is specified for use in RCC applications.

29.2 RCC DSSS BPSK PHY specification

The RCC DSSS BPSK PHY shall employ the BPSK PHY specified in Clause 14, with the exception that the bit-to-chip mapping is changed as shown in Table 29-1.

Table 29-1—RCC DSSS BPSK PHY bit-to-chip mapping

Input bit	Chip values (c_0, c_1, \dots, c_{14})
0	1 1 0 1 0 1 0 1 1 0 0 1 0 0 0
1	0 0 1 0 1 0 1 0 0 1 1 0 1 1 1

30. CMB PHY

30.1 CMB O-QPSK PHY specification

30.1.1 PPDU format for the CMB O-QPSK PHY

30.1.1.1 General

The PPDU shall be formatted as illustrated in Figure 30-1.

Octets: 4	2	3	variable
Preamble	SFD	As defined in 30.1.1.4	PSDU
SHR	PHR		PHY payload

Figure 30-1—Format of CMB O-QPSK PHY PPDU

30.1.1.2 Preamble field

The length of the preamble for the O-QPSK PHY shall be 8 symbols (i.e., 4 octets), where the bits in the Preamble fields are defined in 13.1.2.

30.1.1.3 SFD field

The SFD field shall be formatted as illustrated in Figure 22-3.

30.1.1.4 PHR field

The PHR field is illustrated in Figure 30-2. All multibit fields are unsigned integers and shall be processed MSB first.

Bits: 0	1	2–8	9–15	16–23
Spreading Mode	Rate Mode	Reserved	Frame Length	HCS

Figure 30-2—Format of the PHR for CMB O-QPSK PHY

For CMB operation bands, the Spreading Mode field shall be set to one if DSSS is used for PSDU spreading. Otherwise, the Spreading Mode field should be set to zero.

The Rate Mode field indicates the rate mode used to encode the packet and shall contain one of the values in Table 30-1. Table 30-1 shows the mapping of the Rate Mode field to data rate.

Table 30-1—Rate mode mapping of CMB O-QPSK PHY

Rate mode	Data rate (kb/s)
0	250
1	500

The Frame Length field is an unsigned integer and shall be set to the total number of octets contained in the PSDU. The Frame Length field is transmitted LSB first.

The HCS field is calculated over the first 16 PHR bits (b_0, b_1, \dots, b_{15}), where b_0 is the PHR bit at bit string index 0 and b_{15} is the PHR bit at bit string index 15, as illustrated in Figure 30-2. The HCS field is defined in 22.2.3.

30.1.1.5 PSDU field

The PSDU field carries the payload data of the PHY packet.

30.1.2 Modulation and coding for CMB O-QPSK PHY

30.1.2.1 Reference modulator diagram

Figure 30-3 shows a reference modulator diagram for the CMB O-QPSK PHY.

The inputs to the reference modulator are the bit sequences of the SHR field, the PHR field, and the PSDU field.

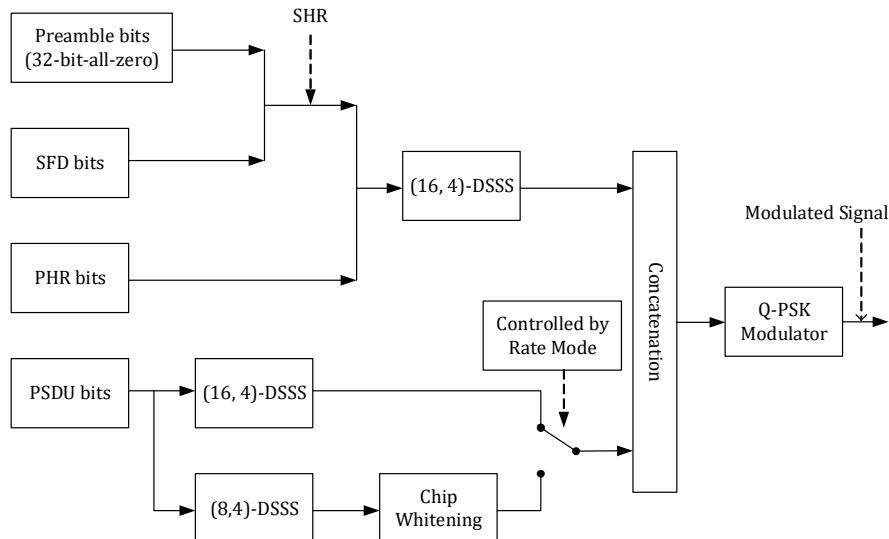


Figure 30-3—Reference diagram of CMB O-QPSK PHY

30.1.2.2 SHR coding and spreading

The SHR spreading is (16,4) DSSS bit-to-chip mapping. The parameters are shown in Table 22-15.

30.1.2.3 PHR coding and spreading

The PHR field spreading is (16,4) DSSS bit-to-chip mapping. The parameters are shown in Table 22-15.

30.1.2.4 PSDU coding and spreading for DSSS

Figure 30-3 shows the signal flow when DSSS is applied to the PSDU, i.e., the spreading mode set to DSSS. The supported PSDU parameters for spreading mode DSSS are shown in Table 30-1.

Depending on the frequency band and rate mode, the output sequence of the bit-to-chip mapper shall be whitened, as described in 30.1.2.6.

The relationship between the rate mode and the data rate parameters of the MCPS-DATA.request primitive is described in Table 8-30 in 8.3.4.

30.1.2.5 DSSS bit-to-chip mapping

DSSS bit-to-chip mapping of (8,4) and (16,4) for CMB O-QPSK PHY shall be specified as Table 22-14 and Table 22-15, respectively, in 22.3.9.

30.1.2.6 Chip whitening

When spreading mode is set to DSSS, the PSDU chip sequence shall be whitened for the frequency bands and rate modes shown in Table 30-2. The PSDU chip sequence shall be whitened according to 22.3.11.

Table 30-2—Chip whitening for DSSS

Frequency band (MHz)	Rate mode
176–214	1
407–425	1
608–630	1

Chip whitening is the modulo-2 addition of a chip of the PSDU at the output of the bit-to-chip mapper with the value of a cyclic m -sequence of length for $m = 9$. This process shall be performed by the transmitter and is described by 22.3.11.

30.1.2.7 Modulation parameters for CMB O-QPSK

A chip value shall be mapped into a binary real-valued symbol out of $\{-1, 1\}$ by the following mapping:

$$\zeta(c) = \begin{cases} -1, & c_k = 0 \\ +1, & c_k = 1 \end{cases}$$

In the CMB operation bands (as defined in 11.1), the raised cosine pulse shape with a roll-off factor of $r = 0.8$, as defined in 13.2.7, shall be used.

30.1.3 CMB O-QPSK PHY RF requirements

30.1.3.1 Operating frequency range

The operating frequency ranges of the CMB O-QPSK PHY are described in Table 11-5.

30.1.3.2 Transmit PSD mask

In general, when operating in the 195 MHz, 416 MHz, and 619 MHz bands, the transmitted spectral products shall be less than the limits specified in Table 13-3 (in 13.3.2) and Table 30-3. For both relative and absolute limits, average spectral power shall be measured using a 100 kHz resolution bandwidth. For the

relative limit, the reference level shall be the highest average spectral power measured within ± 600 kHz of the carrier frequency f_c .

Table 30-3—PSD limitation among channels

Frequency	Relative limit	Absolute limit
$ f - f_c > 1.2$ MHz	-20 dB	-20 dBm

However, some special limitations for spurious radio emissions for medical signal transmissions exist under Chinese radio regulations. The details of these limitations are described in MIIT Doc 423-2005 [B34], Li, et al. [B22], and Li, et al. [B23].

30.1.3.3 Receiver sensitivity

Under the conditions specified in Table 11-30 (in 11.1.8), a compliant device shall be capable of achieving the sensitivity values given in Table 30-4.

Table 30-4—Required receiver sensitivity (dBm) for two rate mode modulation

Frequency band (MHz)	Rate mode	
176–214	-85	-82
407–425	-85	-82
608–630	-85	-82

30.1.3.4 TX-to-RX turnaround time

The CMB O-QPSK PHY shall meet the requirements for TX-to-RX turnaround time as defined in 11.2.2.

30.1.3.5 RX-to-TX turnaround time

The CMB O-QPSK PHY shall meet the requirements for RX-to-TX turnaround time as defined in 11.2.3.

30.1.3.6 EVM definition

CMB O-QPSK transmitters shall have EVM values of less than 35% when measured for 1000 chips. The EVM measurement shall conform to 11.2.4.

30.1.3.7 Transmit center frequency tolerance

The CMB O-QPSK PHY transmit center frequency tolerance shall be ± 40 ppm maximum.

30.1.3.8 Transmit power

The CMB O-QPSK PHY shall be capable of transmitting at a power level of at least -3 dBm.

30.1.3.9 Receiver maximum input level of desired signal

The CMB O-QPSK PHY shall meet the receiver maximum input level as specified in 13.3.11.

30.1.3.10 Receiver ED

The CMB O-QPSK PHY shall provide the receiver ED measurement as described in 11.2.6.

30.1.3.11 LQI

The CMB O-QPSK PHY shall provide the LQI measurement as described in 11.2.7.

30.1.3.12 CCA

The CMB O-QPSK PHY shall use one of the CCA methods as described in 11.2.8.

The detection time (*phyCcaDuration* as defined in 12.3.2) for CCA is 8 symbols.

30.2 CMB GFSK PHY specification

30.2.1 PPDU format for CMB GFSK PHY

30.2.1.1 General

The CMB GFSK PPDU format shall be as specified in 21.2 except for the PHR. The PHR of the CMB GFSK PPDU shall be as specified in 30.2.1.2.

30.2.1.2 Preamble field

The Preamble field shall contain up to 30 repetitions of the 8-bit sequence “01010101” for CMB GFSK.

30.2.1.3 SFD

The SFD for CMB GFSK shall be a 2-octet sequence selected from the list of values shown in Table 30-5. Devices that do not support FEC shall support the SFD associated with uncoded (PHR + PSDU) and may also support the SFD associated with uncoded (PHR + PSDU). Devices that support FEC shall support both SFDs.

The SFD is transmitted starting from the leftmost bit (i.e., starting with b0).

Table 30-5—CMB GFSK PHY SFD values for GFSK

SFD value for coded (PHR + PSDU) (b0–b15)	SFD value for uncoded (PHR + PSDU) (b0–b15)
0110 1111 0100 1110	1001 0000 0100 1110

30.2.1.4 PHR

The format of the PHR is shown in Figure 30-4. All multibit fields are unsigned integers and shall be processed MSB first.

Figure 30-4—Format of the PHR for CMB GFSK

Bits: 0–2	3	4	5–8	9–15
Reserved	FCS Type	Data Whitening	Reserved	Frame Length

The format of the FCS Type, Data Whitening, and Frame Length fields shall be as specified in 20.2.3.

30.2.2 Modulation and coding for CMB GFSK PHY

30.2.2.1 Gaussian filter definition

The transmission pulse shape $p(t)$ for CMB GFSK PHY shall be constrained by the shape of a normalized cross-correlation function $\phi(t)$ with a Gaussian filter whose pulse shape $r(t)$ is as follows:

$$r(t) = \frac{1}{\sqrt{2\pi} \times BT} \exp\left(-\frac{t^2}{2 \times (BT)^2}\right)$$

where

- BT is 0.7
- t is normalized by the symbol duration

where

- B is the 3 dB filter bandwidth
- T is the bit period of the transmission

The normalized cross-correlation $\phi(t)$ between two waveforms, $p(t)$ and $r(t)$, is defined as follows:

$$\phi(t) = \frac{1}{\sqrt{E_r \times E_p}} \times \int_{-\infty}^{\infty} r(t) \times p(t + \tau) dt$$

where E_r and E_p are the energies of $r(t)$ and $p(t)$, respectively.

In order for the CMB GFSK PHY transmitter to be compliant with this standard, the transmitted pulse $p(t)$ shall have a magnitude of the cross-correlation function $|\phi(t)|$ whose main lobe is greater than or equal to 0.96, when integrated over a period of at least from -0.5 to +0.5 normalized symbol duration time.

$$\phi(t) = \frac{1}{\sqrt{E_r \times E_p}} \times \int_{-0.5}^{+0.5} r(t) \times p(t + \tau) dt$$

The modulation for the CMB GFSK PHY shall be a 2-level Gaussian-filtered FSK that meets the transmit spectral mask defined in 30.2.4.5. These requirements can be satisfied automatically when, for all modes (#1 to #5), the BT value of 0.7 is used to generate the Gaussian filter.

Table 30-6 shows the modulation and channel parameters for the standard-defined PHY operating modes for the 195 MHz, 416 MHz, and 619 MHz bands. A device shall support mode #5 and may additionally support modes #1, #2, #3, and #4.

Table 30-6—CMB GFSK modulation and channel parameters

Frequency band	Parameter	Mode #1	Mode #2	Mode #3	Mode #4	Mode #5
174–216 MHz 407–425 MHz 608–630 MHz	Data rate (kb/s)	100	100	200	200	50
	Modulation index	0.5	1.0	0.5	1.0	1.0
	Channel spacing (kHz)	500	500	500	500	500

30.2.2.2 Reference modulator diagram

The functional block diagram in Figure 30-5 is provided as a reference for specifying the CMB GFSK PHY data flow processing functions. Each bit shall be processed using the bit order rules defined in 30.2.1.

When FEC is enabled, the PHR and PSDU shall be processed for coding as a single block of data, as described in 30.2.2.7. When data whitening is enabled, the scrambling shall be applied only over the PSDU, as described in 30.2.3.

All fields in the PPDU shall use the same symbol rate and modulation order, unless otherwise specified elsewhere in this standard.

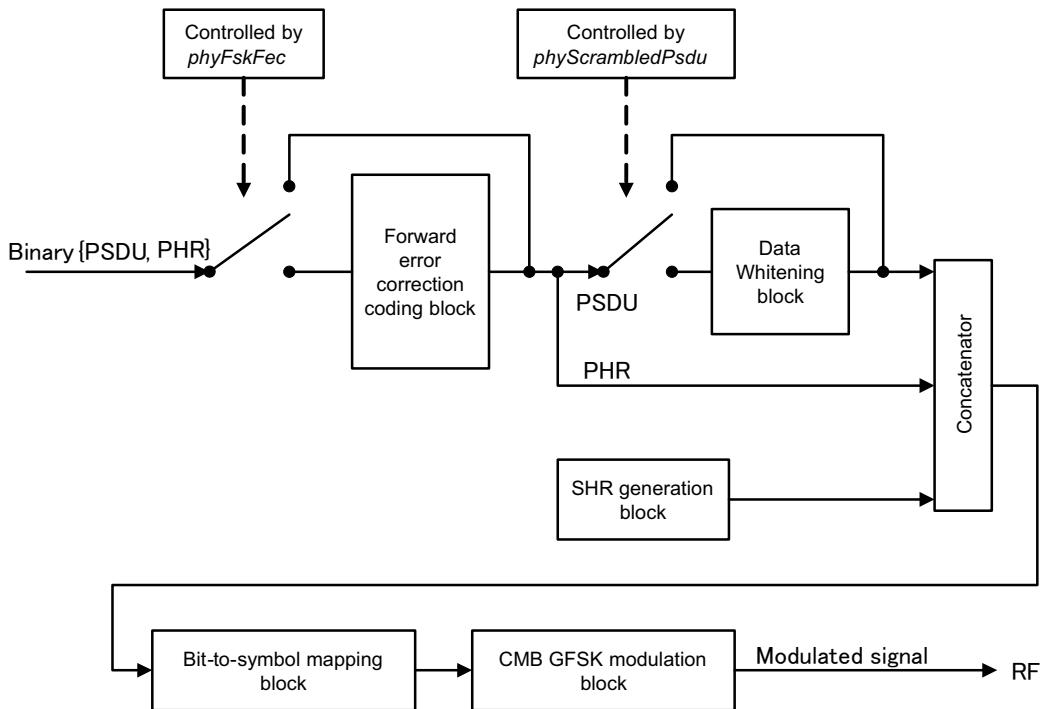


Figure 30-5—CMB GFSK FEC, data whitening, and modulator functions

30.2.2.3 Bit-to-symbol mapping

The nominal frequency deviation, Δf , shall be as follows:

$$\Delta f = \left(\frac{\text{symbol rate} \times \text{modulation index}}{2} \right)$$

The symbol encoding for the CMB GFSK PHY is shown in Table 30-7, where the frequency deviation, f_{dev} , is equal to Δf for filtered 2-FSK.

Table 30-7—CMB GFSK symbol encoding

2-level	
Symbol (binary)	Frequency deviation
0	$-f_{\text{dev}}$
1	$+f_{\text{dev}}$

30.2.2.4 Modulation quality

The modulation quality for the CMB GFSK PHY shall be as specified as 20.3.4.

30.2.2.5 Frequency deviation tolerance

The frequency deviation tolerance of the CMB GFSK PHY shall be as specified in 20.3.4.2.

30.2.2.6 Zero crossing tolerance

The zero crossing specification for the CMB GFSK PHY shall be as specified as 2-FSK, as described in 20.3.4.3.

30.2.2.7 FEC

FEC is optional. If the SFD indicates that FEC is used, as described in Table 30-5, then the FEC is applied to the PHR and PSDU as a single block of data.

Two types of FEC may be applied: an RSC or an NRNSC. The use of RSC or NRNSC coding shall be controlled by the PIB attribute *phyFskFecScheme*, as defined in 12.3.10.

When the SFD value indicates a coded packet, FEC as specified in 20.3.5 shall be employed on the PHR and PSDU bits.

30.2.3 Data whitening for CBM GFSK PHY

Data whitening for the CMB GFSK PHY shall be as specified as 20.4.

30.2.4 CMB GFSK PHY RF requirements

30.2.4.1 Operating frequency range

The CMB GFSK PHY operates in the bands given in Table 11-27.

30.2.4.2 RF tolerance

The single-sided clock frequency tolerance at the transmitter shall be ± 20 ppm.

30.2.4.3 Receiver sensitivity

Receiver sensitivity for the CMB GFSK PHY shall be as specified as 20.6.7.

30.2.4.4 Transmitter symbol rate

The transmitter symbol rate tolerance for the CMB GFSK PHY shall be as specified in 20.6.5.

30.2.4.5 Transmit spectral mask

NOTE—In the presence of additional regulatory restrictions, the CMB device has to respect both the regulatory requirements and the mask defined in this subclause.

For all CMB GFSK transmit spectral masks, the interim transmit spectral mask shall have:

- 0 dBr within $\pm 1 \times$ symbol rate frequency (in hertz) range of the center frequency
- -10 dBr within a range of from $1.5 \times$ symbol rate frequency (in hertz) to $1 \times$ symbol rate frequency (in hertz) apart from the center frequency
- -25 dBr within a range of from $1.5 \times$ symbol rate frequency (in hertz) to $2 \times$ symbol rate frequency (in hertz) apart from the center frequency
- -35 dBr at frequency offset apart from more than $2 \times$ symbol rate frequency (in hertz) from the center frequency

where dBr is defined as relative power to the measured average transmission power within $\pm 1 \times$ symbol rate frequency (in hertz) range of the center frequency.

Table 30-8 shows this spectral mask for all CMB GFSK PHYs.

Table 30-8—Transmit spectral mask for CMB GFSK PHY

Normalized frequency by symbol rate (frequency [Hz]/ symbol rate [b/s])	PSD (dBr)
-2 and below	-35
from -2 to -1.5	-25
from -1.5 to -1	-10
from -1 to +1	0
from +1 to 1.5	-10
from +1.5 to +2	-25
+2 and above	-35

30.2.4.6 TX-to-RX turnaround time

The CMB GFSK PHY shall meet the requirements for TX-to-RX turnaround time as defined in 11.2.2.

30.2.4.7 RX-to-TX turnaround time

The CMB GFSK PHY shall meet the requirements for RX-to-TX turnaround time as defined in 11.2.3.

30.2.4.8 Transmit power

The CMB GFSK PHY shall be capable of transmitting at a power level of at least -3 dBm.

30.2.4.9 Receiver ED

The CMB GFSK PHY shall provide the receiver ED measurement as described in 11.2.6.

30.2.4.10 LQI

The CMB GFSK PHY shall provide the LQI measurement as described in 11.2.7.

30.2.4.11 CCA

The CMB GFSK PHY shall use one of the CCA methods as described in 11.2.8.

31. TASK PHY

31.1 General

The TASK PHY employs ternary sequence spreading followed by amplitude shift keying (ASK) modulation.

For the TASK PHY, the symbol duration parameters for MAC and PHY timing shall be set as given in Table 31-1 for different bands of operations. Symbol period is defined as the value of one symbol duration.

Table 31-1—TASK symbol duration used for MAC and PHY timing parameters

Frequency band (MHz)	Chip rate (Mchip/s)	Symbol duration (μs)
433.050–434.790	0.25	64
470–510	0.25	64
779–787	0.6	26.667
863–876	0.6	26.667
902–928	0.6	26.667
2400–2483.5	1	16

31.2 PPDU

31.2.1 General

The PPDU structure is presented so that the leftmost field of the PPDU shall be transmitted or received first. For all multi-octet fields, the leftmost octet represents the least significant octet, and for each octet, the leftmost bit represents the LSB. Unless otherwise stated, all multi-octet fields shall be transmitted or received least significant octet first, and each octet shall be transmitted or received LSB first.

31.2.2 PPDU format

31.2.2.1 General

The format for the PPDU shall be as illustrated in Figure 13-1.

31.2.2.2 SHR field

31.2.2.2.1 Structure of the SHR field

The SHR field shall have the Preamble field followed by the SFD field as illustrated in Figure 13-2. The formats of the individual Preamble and SFD fields are explained in the following subclauses.

31.2.2.2.2 Preamble field

The Preamble field shall have a unique ternary base sequence of length 32 chips repeated 8 times. This 32-chip base sequence is given by [1 0 –1 0 0 –1 0 –1 1 0 1 0 0 –1 0 1 1 0 1 0 0 –1 0 1 –1 0 1 0 0 1 0 1].

In the coherent reception mode, the preamble is equivalent to a string of 8 bits spread by a sequence with a spreading factor of 32, and in the noncoherent reception mode, the preamble is equivalent to a string of 32 bits spread by a sequence with a spreading factor of 8.

31.2.2.2.3 SFD field

The SFD field indicates the end of the SHR field. The SFD field shall consist of a pattern of 8 bits, [0 1 0 1 1 0 0 1]. The bits in this field are mapped onto a ternary spreading code composed of two orthogonal ternary sequences. The bit-to-sequence mapping shall be as given in Table 31-2.

Table 31-2—Spreading of the SFD field

SFD bit	Bit-to-sequence mapping
0	[0 –1 0 1 1 0 –1 0]
1	[1 0 –1 0 0 –1 0 1]

31.2.2.3 PHR Field

31.2.2.3.1 Structure of the PHR field

The PHR shall be constructed as shown in Figure 31-1.

Bits: 0–6	7	8–10	11	12–15
Length	Reserved	MCS	Reserved	HCS

Figure 31-1—Format of the PHR field

31.2.2.3.2 Length field

The Length field specifies the total number of octets contained in the PSDU.

31.2.2.3.3 MCS field

The MCS field specifies the modulation format and the FEC to be applied on the PSDU. Four modulation formats and two FECs are provided. Valid values of the MCS field and the corresponding mapping of the modulation format and the FECs are given in Table 31-3.

Table 31-3—Mapping of the MCS field

MCS field (b8, b9, b10)	Modulation format	FEC
(0, 0, 0)	1/1-TASK	Bose Chaudhuri Hocquenghem (BCH)
(1, 0, 0)	2/4-TASK	BCH with interleaving
(0, 1, 0)	3/8-TASK	BCH with interleaving
(1, 1, 0)	5/32-TASK	BCH with interleaving
(0, 0, 1)	1/1-TASK	BCH+SiPC

Table 31-3—Mapping of the MCS field (*continued*)

MCS field (b8, b9, b10)	Modulation format	FEC
(1, 0, 1)	2/4-TASK	BCH with interleaving + SiPC
(0, 1, 1)	3/8-TASK	BCH with interleaving + SiPC
(1, 1, 1)	5/32-TASK	BCH with interleaving + SiPC

NOTE—“BCH + SiPC” indicates the concatenated code generated by BCH code as the outer code and the SiPC as the inner code. “BCH with interleaving + SiPC” indicates concatenated code generated by BCH with interleaving as the outer code and the SiPC as the inner code.

31.2.2.3.4 HCS field

The PHY header shall be protected with a 4-bit HCS. The HCS shall be generated by taking the one’s complement of the remainder obtained from the modulo-2 division of bits b0–b11 of the PHY header by the following polynomial:

$$g(x) = 1 + x + x^4$$

The HCS field shall be generated by processing the bits b0–b11 in the transmit order. In the HCS field, the LSB of the HCS, b12, shall be transmitted first. This is illustrated in Figure 31-2. The registers shall be initialized to all ones.

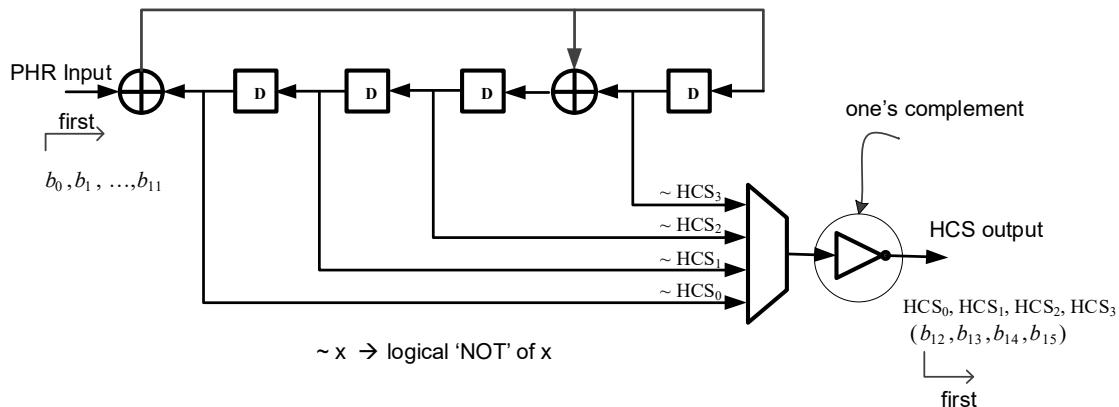


Figure 31-2—Generation of the HCS field

31.2.2.3.5 Spreading of PHR field

Similar to the spreading performed on the SFD field, bits in the PHR field are also mapped onto a ternary spreading code comprising two orthogonal ternary sequences. The bit-to-sequence mapping shall be as given in Table 31-4.

Table 31-4—Spreading of the PHR field

PHR bit	Bit-to-sequence mapping
0	[0 -1 0 1 1 0 -1 0]
1	[1 0 -1 0 0 -1 0 1]

31.2.2.4 PSDU field

The PSDU field carries the payload of a PPDU.

31.2.3 Generation of PPDU signal

For a given MCS, the PPDU signal shall be generated by the following procedure:

- Construct the Preamble field (31.2.2.2), the SFD field (31.2.2.3), and the PHR field (31.2.2.3).
- Apply the modulation format and FEC on the PSDU as determined by the MCS of the PHR field. Perform pseudo-random chip inversion on the resultant chips to obtain the DATA field. This process is described in 31.4.
- Concatenate the Preamble field, the spread SFD field, the PHR field, and the DATA field, according to the order given in 31.2.2, to generate the PPDU.
- Pass the resultant chip sequence of the PPDU through the modulation block as described in 31.5, followed by the Gaussian pulse shaping filter as described in 31.6.

The reference modulator diagram for generating a PPDU signal for the TASK PHY is as depicted in Figure 31-3.

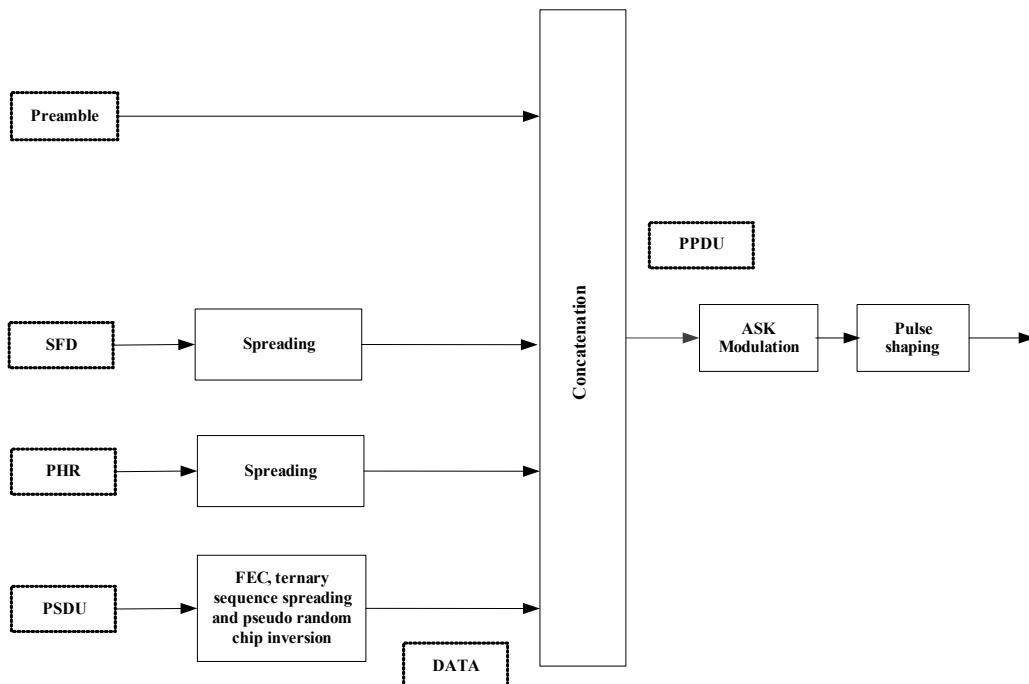


Figure 31-3—Reference modulator diagram—generation of PPDU signal

31.3 MCS mode, MCS, data rates, and related parameters

31.3.1 MCS mode

The MCS used for the PSDU in a frame is determined by the MAC in an implementation-dependent manner. The MCS mode specifies modulation and coding schemes to be applied on the PSDU. In any given frequency band of operation, eight MCS modes (0–7) are defined based on the data rates. The MCS mode and the corresponding data rates for different frequency bands are provided in Table 31-5, Table 31-6, and Table 31-7. The values presented in the data rate column of each of these tables correspond to the DataRate parameter as used in MCPS-DATA.request primitive as described in 8.3.4. Also, for each MCS, the parameters such as modulation order (M) and spreading sequence length (L) are given in these tables.

31.3.2 Data rates in the 2450 MHz band

The supported data rates and related parameters for 2450 MHz band are given in Table 31-5.

Table 31-5—PSDU modulation and coding formats and the supported data rates in 2450 MHz band

MCS mode	Modulation format	Coding format	Chip rate (Mchip/s)	M (Bits/data symbol)	L (Chips/data symbol)	Code rate	Data rate (kb/s)
0	1/1-TASK	BCH	1	1	1	51/63	809.52
1	2/4-TASK	BCH with interleaving	1	2	4	51/63	404.76
2	3/8-TASK	BCH with interleaving	1	3	8	51/63	303.57
3	5/32-TASK	BCH with interleaving	1	5	32	51/63	126.48
4 (Optional)	1/1-TASK	BCH+SiPC	1	1	1	408/567	719.57
5 (Optional)	2/4-TASK	BCH with interleaving +SiPC	1	2	4	408/567	359.78
6 (Optional)	3/8-TASK	BCH with interleaving +SiPC	1	3	8	408/567	269.84
7 (Optional)	5/32-TASK	BCH with interleaving +SiPC	1	5	32	408/567	112.43

31.3.3 Data rates in the 780 MHz, 863 MHz, and 915 MHz bands

The supported data rates and related parameters are given in Table 31-6.

Table 31-6—PSDU modulation and coding formats and the supported data rates in 780 MHz, 863 MHz, and 915 MHz bands

MCS mode	Modulation format	Coding format	Chip rate (Mchip/s)	M (Bits/data symbol)	L (Chips/data symbol)	Code rate	Data rate (kb/s)
0	1/1-TASK	BCH	0.6	1	1	51/63	485.71
1	2/4-TASK	BCH with interleaving	0.6	2	4	51/63	242.85
2	3/8-TASK	BCH with interleaving	0.6	3	8	51/63	182.14
3	5/32-TASK	BCH with interleaving	0.6	5	32	51/63	75.89
4 (Optional)	1/1-TASK	BCH+SiPC	0.6	1	1	408/567	431.74
5 (Optional)	2/4-TASK	BCH with interleaving +SiPC	0.6	2	4	408/567	215.87
6 (Optional)	3/8-TASK	BCH with interleaving +SiPC	0.6	3	8	408/567	161.90
7 (Optional)	5/32-TASK	BCH with interleaving +SiPC	0.6	5	32	408/567	67.46

31.3.4 Data rates in the 433 MHz and 470 MHz bands

Available data rates when operating in the 433 MHz and 470 MHz bands are shown in Table 31-7.

Table 31-7—PSDU modulation and coding formats and the supported data rates in 433 MHz and 470 MHz bands

MCS mode	Modulation format	Coding Format	Chip rate (Mchip/s)	M (Bits/data symbol)	L (Chips/data symbol)	Code rate	Data rate (kb/s)
0	1/1-TASK	BCH	0.25	1	1	51/63	202.38
1	2/4-TASK	BCH with interleaving	0.25	2	4	51/63	101.19
2	3/8-TASK	BCH with interleaving	0.25	3	8	51/63	75.89
3	5/32-TASK	BCH with interleaving	0.25	5	32	51/63	31.62

Table 31-7—PSDU modulation and coding formats and the supported data rates in 433 MHz and 470 MHz bands (continued)

MCS mode	Modulation format	Coding Format	Chip rate (Mchip/s)	M (Bits/data symbol)	L (Chips/ data symbol)	Code rate	Data rate (kb/s)
4 (Optional)	1/1-TASK	BCH+SiPC	0.25	1	1	408/567	179.89
5 (Optional)	2/4-TASK	BCH with interleaving +SiPC	0.25	2	4	408/567	89.94
6 (Optional)	3/8-TASK	BCH with interleaving +SiPC	0.25	3	8	408/567	67.46
7 (Optional)	5/32-TASK	BCH with interleaving +SiPC	0.25	5	32	408/567	28.10

31.4 FEC, ternary sequence spreading, and pseudo-random chip inversion

31.4.1 General

The functional block diagrams in Figure 31-4 and Figure 31-5 provide a reference for specifying the TASK PHY modulation and coding functionalities for the PSDU. The following two modes of operation are based on the FEC mechanisms:

- *Mandatory mode*: (MCS mode 0, 1, 2, or 3) BCH with interleaving shall be used for the FEC. The reference diagram for this mode is provided in Figure 31-4.
- *Optional mode*: (MCS mode 4, 5, 6, or 7) Concatenation of BCH with interleaving and single parity check (SiPC) shall be used for the FEC. The reference diagram for this mode is provided in Figure 31-5.

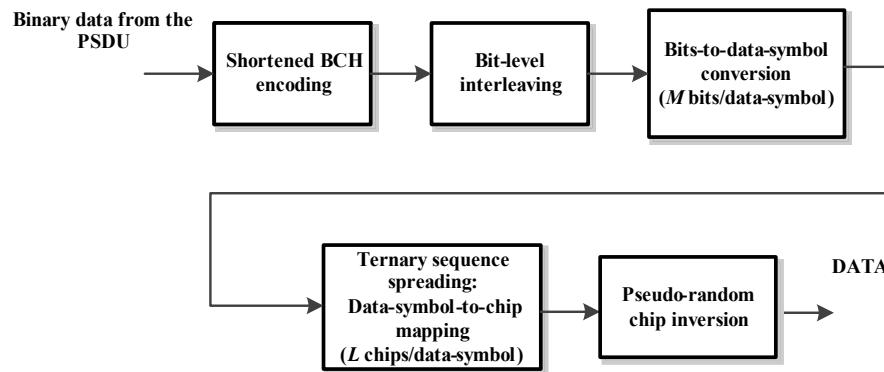


Figure 31-4—FEC, ternary sequence spreading, and pseudo-random chip inversion: mandatory mode

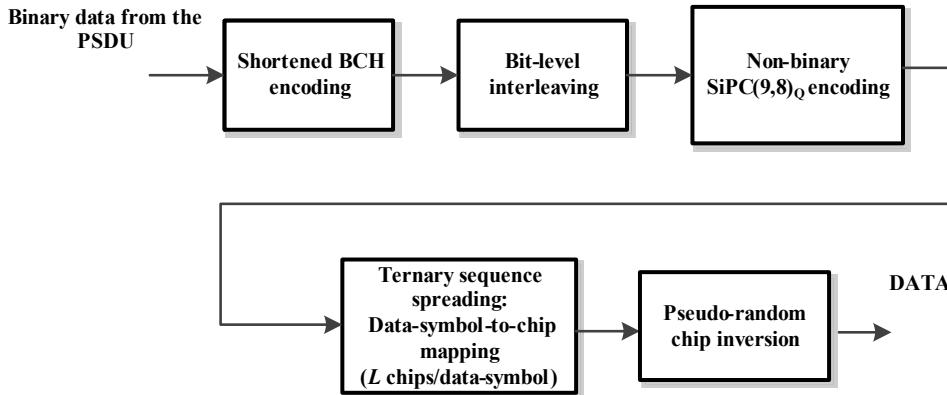


Figure 31-5—FEC, ternary sequence spreading, and pseudo-random chip inversion: optional mode

31.4.2 FEC codes

31.4.2.1 Shortened BCH codes with bit-level interleaving

31.4.2.1.1 Calculation of the BCH-related parameters

Parameters for shortened BCH (63, 51) encoding shall be calculated using the following procedure:

- Compute the number of bits in the PSDU, N_{PSDU} :

$$N_{\text{PSDU}} = \text{Length} \times 8$$

- Compute the total number of message blocks to be encoded, M_B :

$$M_B = \left\lceil \frac{N_{\text{PSDU}}}{51} \right\rceil$$

where $\lceil x \rceil$ denotes the smallest integer greater than or equal to x .

- Compute the length of the shortened message block, K_{short} :

$$K_{\text{short}} = \left\lceil \frac{N_{\text{PSDU}}}{M_B} \right\rceil$$

- Compute the shortening length of the code, l :

$$l = 51 - K_{\text{short}}$$

- Compute the length of the shortened BCH code, N_{short} :

$$N_{\text{short}} = 63 - l$$

- Compute the number of zero pad bits, Z , to be appended to the uncoded PSDU block:

$$Z = M_B K_{\text{short}} - N_{\text{PSDU}}$$

where it can be shown that $Z \leq M_B$.

g) Compute the length of the encoded PSDU, N_{coded} :

$$N_{\text{coded}} = M_B N_{\text{short}}$$

31.4.2.1.2 Zero padding

Zero pad bits are added to the uncoded PSDU to provide uniformity in the length of message blocks before encoding, i.e., to create M_B message blocks of block length K_{short} bits. First, the uncoded PSDU of length N_{PSDU} bits should be packed as follows:

- Create Z message blocks of length $(K_{\text{short}} - 1)$ bits from the first $(K_{\text{short}} - 1)Z$ bits of the PSDU.
- Create $(M_B - Z)$ message blocks of length K_{short} bits, using the remaining $(M_B - Z)K_{\text{short}}$ bits.

The zero padding is performed by appending one zero bit at the end of each of the first Z message blocks.

31.4.2.1.3 BCH encoding

The generator polynomial for the BCH (63, 51) codes, with error correcting capability, $t = 2$, is as follows:

$$g(x) = 1 + x^3 + x^4 + x^5 + x^8 + x^{10} + x^{12}$$

Shortened BCH codes, denoted by BCH $(63 - l, 51 - l)$, can be obtained from the BCH (63, 51) code for any given shortening length, l , $1 \leq l < 51$.

For a given message block of length, K_{short} , the message polynomial is represented as follows:

$$m(x) = \sum_{i=0}^{K_{\text{short}}-1} m_i x^i$$

where $m_0, \dots, m_{K_{\text{short}}-1}$ are the message bits and are the elements of GF(2).

For a given message polynomial, $m(x)$, the parity polynomial, $p(x)$, is computed as follows:

$$p(x) = \sum_{k=0}^{11} p_k x^k = \text{mod}(x^{12} m(x), g(x))$$

where p_0, \dots, p_{11} are the parity bits.

The order of the message and parity bits shall be as follows:

- For the message bits, $m_{K_{\text{short}}-1}$ shall be the first bit to be transmitted in the message block, and m_0 shall be the last bit to be transmitted.
- For parity bits, p_{11} is the first parity bit to be transmitted, and p_0 is the last parity bit to be transmitted.

In generating the codeword, parity bits shall be appended to the right of the message block so that the message bits are transmitted first and then followed by the parity bits. This procedure is illustrated in Figure 31-6.

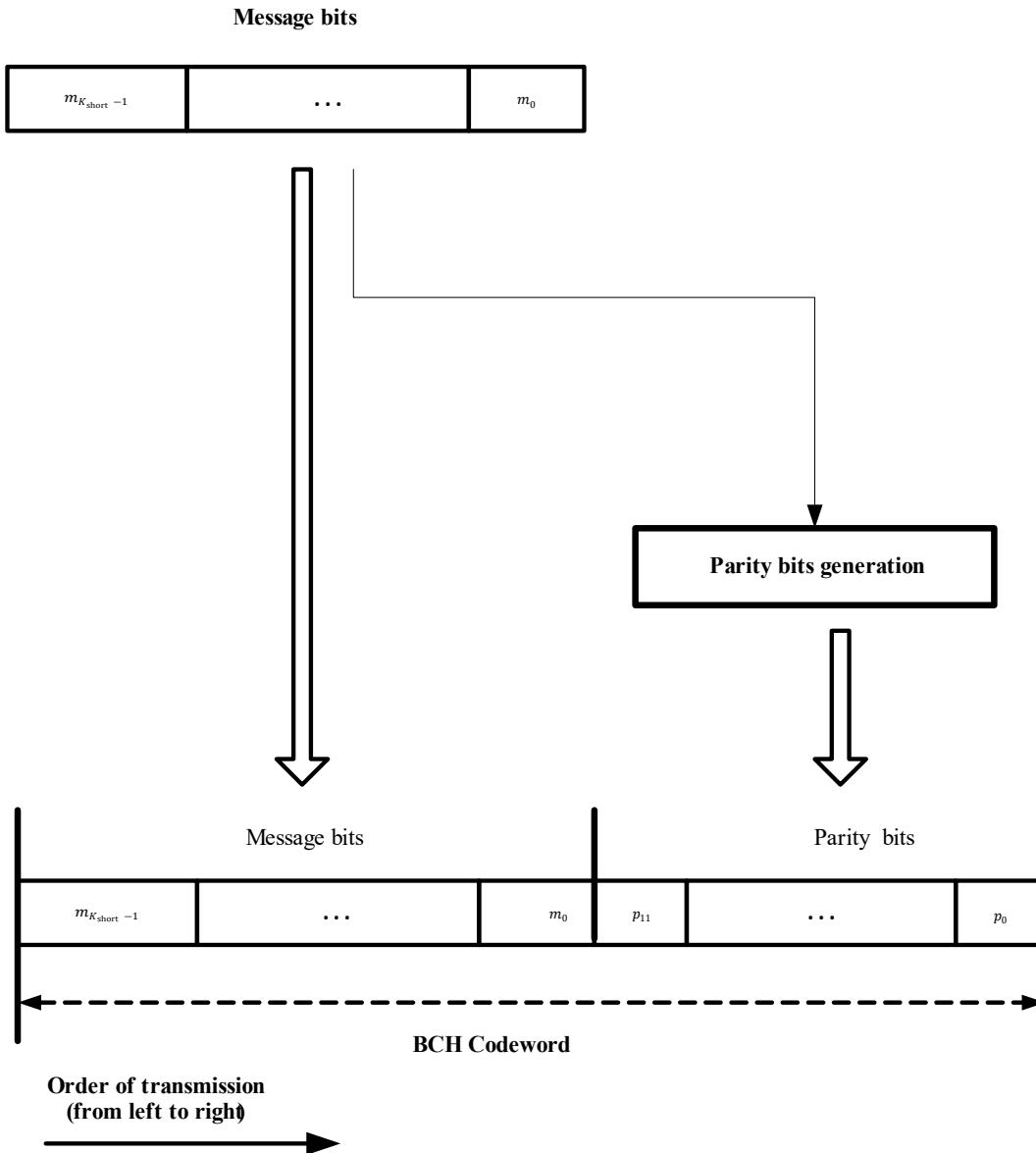


Figure 31-6—Generation of the BCH codeword for a given message block

31.4.2.1.4 Bit-level interleaving

Bit-level interleaving shall be used in conjunction with the shortened BCH codes to make encoded data resilient to bit errors in the event of data symbol errors. For a given codeword length N_{short} and an interleaving depth d , the following procedure is followed:

- Collect d blocks of codewords.
- Write them row-wise in a $d \times N_{\text{short}}$ dimensional array.
- Read the array column-wise, and output the data sequentially.

The pictorial representation of the interleaving procedure is illustrated in Figure 31-7. Here, $b_{i,j}$ denotes the j -th transmitted bit of the i -th BCH codeword. That is, $b_{i,1}$ and $b_{i,N_{\text{short}}}$ denote $m_{K_{\text{short}}}$ and p_0 of the i -th BCH codeword, respectively.

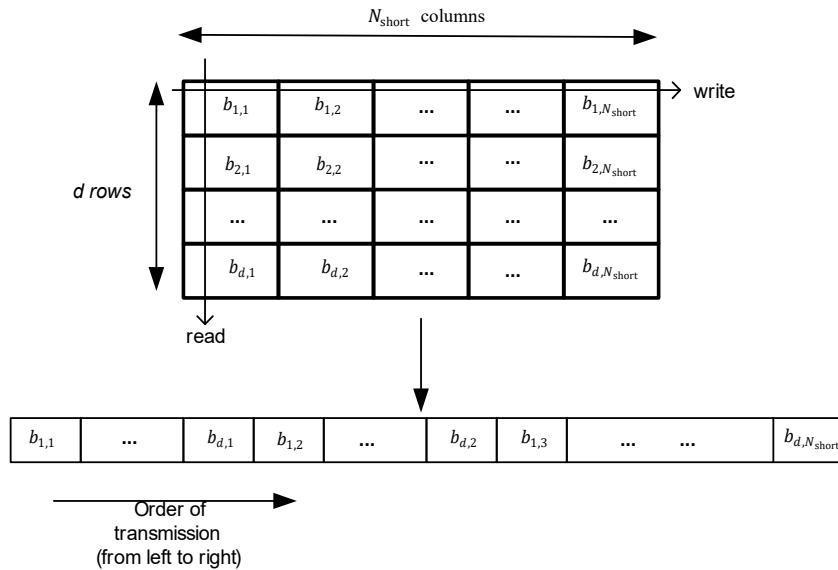


Figure 31-7—Depth- d interleaving for d codewords of length N_{short}

Parameters for bit-level interleaving shall be calculated using the following procedure:

- For a given MCS, with a modulation order M , choose the initial interleaving depth, $d = M$.
- Calculate the residual interleaving depth, d_R :

$$d_R = \text{mod}(M_B, d)$$

- Calculate the number of interleaving blocks, N_I :

$$N_I = \frac{M_B}{d}$$

The bit-level interleaving for the encoded PSDU shall be performed by following the steps outlined in Table 31-8. The maximum interleaving depth, d_{max} , supported by the device shall be defined as $d_{\text{max}} = 5$.

Table 31-8—Interleaving depth vector and corresponding number of interleaving blocks

Condition		Interleaving depth vector	
$d_R = 0$		Apply depth d interleaving for N_I blocks.	
$d_R \neq 0$	$M_B < d$		Apply depth d_R interleaving for N_I blocks.
	$M_B > d$	Apply depth d interleaving for $(N_I - 2)$ blocks and depth $(d + d_R)$ interleaving on the remaining $(d + d_R)$ codewords for the $(N_I - 1)$ th and N_I th blocks.	
		Apply depth d interleaving for $(N_I - 2)$ blocks, depth $\lceil (d + d_R)/2 \rceil$ interleaving for the $(N_I - 1)$ th block, and depth $\lfloor (d + d_R)/2 \rfloor$ interleaving for N_I th block.	

31.4.2.1.5 Bits-to-data-symbol conversion

Prior to the bits-to-data-symbol conversion, the encoded and interleaved PSDU data shall be padded with zeros to align the symbol boundary. The required number of zero padding bits, M_{zero} , shall be determined as follows:

$$M_{\text{zero}} = M \left\lceil \frac{N_{\text{coded}}}{M} \right\rceil - N_{\text{coded}}$$

where M is the modulation order (bits per data-symbol) of the given modulation format as given in Table 31-5, Table 31-6, and Table 31-7.

These M_{zero} bits are appended to the end of the PSDU after BCH encoding and bit-level interleaving and then transmitted last.

The bits-to-data-symbol conversion shall be performed by converting the input bit stream into a sequence of M -tuples, where M -tuple is a block of M consecutive bits. The data symbols shall be generated by mapping each M -tuple to a unique element in the Q -ary alphabet $A = \{0, 1, 2, \dots, Q-1\}$, where Q is the constellation size.

31.4.2.2 Single parity check (SiPC) codes

31.4.2.2.1 General

Nonbinary SiPC $(k+1, k)_Q$ code is defined as follows: SiPC $(k+1, k)_Q$ is a $(k+1)$ length block code over GF(Q), with single-symbol error correcting capability, consisting of k message symbols and one parity check symbol. For MCS modes 4, 5, 6, and 7, FEC shall be the concatenation of BCH with interleaving as the outer code and SiPC $(9, 8)$ code as the inner code. These modes are optional. SiPC $(9, 8)$ encoding on the data-symbols shall be performed as described in 31.4.2.2.2.

31.4.2.2.2 SiPC encoding procedure

First, bits from the interleaving block are packed into a sequence of M -tuples. These M -tuples are then converted into message symbols by uniquely mapping them onto the elements of GF(Q). Then these message symbols are segregated into M_B message blocks, each consisting of 8 message symbols (over GF(Q)). SiPC encoder encodes each message block as follows:

- a) Given message block of message symbols, $u_0, \dots, u_7 \in \text{GF}(Q)$, the encoder generates the parity check symbol, w :

$$w = \sum_{n=0}^7 u_n$$

where the summation is taken over GF(Q).

- b) The SiPC codeword is generated by appending the parity check symbol to the end of the message block.

Once the codewords are generated, the coded symbols, which are the elements of GF(Q), are converted into data symbols by uniquely mapping them onto the Q -ary alphabet $A = \{0, 1, 2, \dots, Q-1\}$.

The order of transmission shall be such that the message symbols are transmitted first and then followed by the parity symbol. This transmission order is illustrated in Figure 31-8.

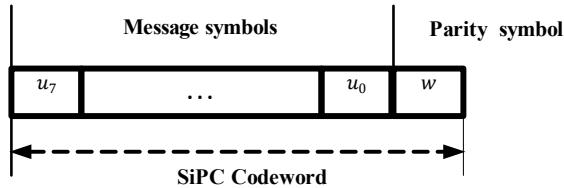


Figure 31-8—Generation of SiPC codeword for a given message block

31.4.3 Ternary sequence spreading: Data-symbol-to-chip conversion

31.4.3.1 General

Ternary sequence spreading is performed by a process of mapping each data symbol to a unique sequence of chips. The mapping is determined by the modulation format specified by the MCS field. The parameters for different modulation formats are given in 31.4. For a modulation format with the constellation size, Q , and the spreading sequence length, L , this stage maps data symbols from $A = \{0, 1, \dots, Q - 1\}$ to a set of L -length ternary sequences, C . Subclauses 31.4.3.2 through 31.4.3.5 outline the data-symbol-to-chip mapping for different modulation formats.

Chip transmission order is as follows: For an L -length chip-sequence, $c_m = [c_m(0), \dots, c_m(L - 1)]$, $c_m(0)$ shall be transmitted first, and $c_m(L - 1)$ shall be transmitted last.

31.4.3.2 1/1-TASK

The data-symbol-to-chip mapping for 1/1-TASK shall be performed as given in Table 31-9.

Table 31-9—Data-symbol-to-chip mapping for 1/1-TASK

1-tuple	Data symbol $m \in A$	Sequence $c_m \in C$
0	0	0
1	1	1

31.4.3.3 2/4-TASK

The data-symbol-to-chip mapping for 2/4-TASK shall be performed as given in Table 31-10.

Table 31-10—Data-symbol-to-chip mapping for 2/4-TASK

2-tuple	Data symbol $m \in A$	Sequence $c_m \in C$
00	0	[1 0 0 0]
10	1	[0 -1 0 0]
01	2	[0 0 0 1]
11	3	[0 0 -1 0]

31.4.3.4 3/8-TASK

The data-symbol-to-chip mapping for 3/8-TASK shall be performed as given in Table 31-11. The ternary sequences for mapping shall be obtained as follows:

$$c_0 = [0 \ 0 \ 0 \ 1 \ -1 \ 0 \ 1 \ 1]$$

c_m = cyclic shifted c_0 by m locations to the right, for $m = 1, \dots, 7$

Table 31-11—Data-symbol-to-chip mapping for 3/8-TASK

3-tuple	Data symbol $m \in A$	Ternary sequence $c_m \in C$
000	0	c_0
100	1	c_1
110	2	c_2
010	3	c_3
011	4	c_4
111	5	c_5
101	6	c_6
001	7	c_7

31.4.3.5 5/32-TASK

The data-symbol-to-chip mapping for 5/32-TASK shall be performed as given in Table 31-12. The ternary sequences for mapping shall be obtained as follows:

$$c_0 = [-1 \ 0 \ 0 \ 1 \ 0 \ 1 \ -1 \ 0 \ -1 \ -1 \ 1 \ -1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 0 \ 0 \ 1 \ 0 \ 0 \ 1 \ 1 \ -1 \ 0 \ 0 \ 0 \ 0 \ 0 \ 1 \ 1]$$

c_m = cyclic shifted c_0 by m locations to the right, for $m = 1, \dots, 31$

Table 31-12—Data symbol to chip mapping for 5/32-TASK

5-tuple	Data symbol $m \in A$	Ternary sequence $c_m \in C$
00000	0	c_0
10000	1	c_1
11000	2	c_2
01000	3	c_3
01100	4	c_4
11100	5	c_5
10100	6	c_6

Table 31-12—Data symbol to chip mapping for 5/32-TASK (continued)

5-tuple	Data symbol $m \in A$	Ternary sequence $c_m \in C$
00100	7	c_7
00110	8	c_8
10110	9	c_9
11110	10	c_{10}
01110	11	c_{11}
01010	12	c_{12}
11010	13	c_{13}
10010	14	c_{14}
00010	15	c_{15}
00011	16	c_{16}
10011	17	c_{17}
11011	18	c_{18}
01011	19	c_{19}
01111	20	c_{20}
11111	21	c_{21}
10111	22	c_{22}
00111	23	c_{23}
00101	24	c_{24}
10101	25	c_{25}
11101	26	c_{26}
01101	27	c_{27}
01001	28	c_{28}
11001	29	c_{29}
10001	30	c_{30}
00001	31	c_{31}

31.4.4 Pseudo-random chip inversion

31.4.4.1 General

The pseudo-random chip inversion shall be performed only on the chips composing the Data field of the PSDU. The operation shall be clocked at the chip rate. This block consists of three main steps as illustrated in Figure 31-9.

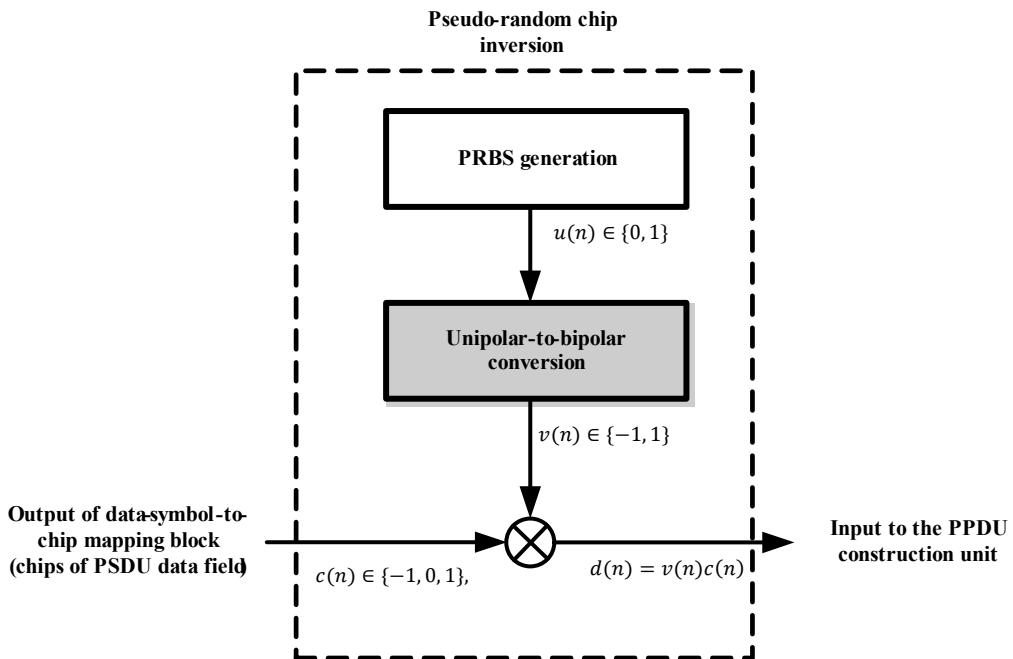


Figure 31-9—Schematic of the pseudo-random chip inversion stage

31.4.4.2 PRBS generation

The pseudo-random binary sequence generated by the PRBS generator shall be equivalent to the output of a 16-bit scrambler, with the generator polynomial (see 16.3.2):

$$G(x) = 1 + x^{14} + x^{15}$$

A reference shift register implementation of the PRBS generator is illustrated in Figure 31-10.

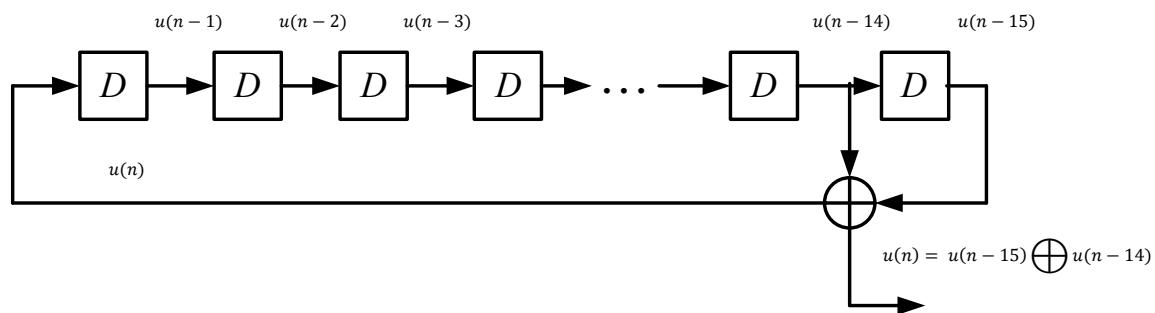


Figure 31-10—Linear feedback shift-register-based implementation of the PRBS generator

The PRBS output is generated recursively as follows:

$$u(n) = u(n-14) \oplus u(n-15), \quad n = 0, 1, 2, \dots$$

where \oplus is the modulo-2 addition operator.

The initialization vector of the PRBS is denoted as follows:

$$\mathbf{u}_{\text{init}} = [u(-15), u(-14), \dots, u(-1)]$$

The PRBS generator shall be initialized with the following vector:

$$\mathbf{u}_{\text{init}} = [1 \ 1 \ 1 \ 0 \ 0 \ 0 \ 1 \ 0 \ 1 \ 1 \ 0 \ 1 \ 1 \ 0 \ 1]$$

31.4.4.3 Unipolar-to-bipolar conversion

The output of the PRBS generator $u(n)$, which is a unipolar binary sequence, shall be converted to bipolar binary sequence, $v(n)$, through the following operation:

$$v(n) = 2u(n) - 1$$

where

$$v(n) = \begin{cases} 1 & \text{if } u(n) = 1 \\ -1 & \text{if } u(n) = 0 \end{cases}$$

31.4.4.4 Chip inversion

The polarities of the chips shall be inverted as follows:

$$d(n) = v(n)c(n), \quad c(n) \in \{-1, 0, 1\}, \quad n = 0, 1, 2, \dots$$

where $\{c(n), n = 0, 1, 2, \dots\}$ is the chip sequence.

At the coherent receiver, to recover the polarity of chips, the PRBS generator shall be initialized with the same initialization vector. On the other hand, the noncoherent receiver does not need to be equipped with the PRBS generator.

31.5 Modulation

The sequence of chips composing the PPDU is modulated using ASK with binary phase shifts. Specifically, the modulation is performed by the following mapping:

$$A_n = \begin{cases} +A & \text{when } d(n) = +1 \\ 0 & \text{when } d(n) = 0 \\ -A & \text{when } d(n) = -1 \end{cases}$$

where

$\{d(n)\}$ is the chip sequence of the PPDU

A_n is the amplitude of the n -th chip

A is the transmit voltage level

The ASK modulation is followed by Gaussian pulse shaping. The chips are generated at the rate of 1 Mchip/s for 2450 MHz band; 600 kchip/s for 780 MHz, 863 MHz, and 915 MHz bands; and 250 kchip/s for 433 MHz and 470 MHz bands.

31.6 Pulse shaping

The modulated signal shall be filtered to meet the transmit PSD masks, as defined in 31.8.1, and the EVM, as defined in 31.8.6. Each baseband chip is represented by a Gaussian pulse, with a bandwidth-time product of $BT_{\text{chip}} = 0.3\text{--}0.5$, where T_{chip} is the chip duration ($T_{\text{chip}} = 1/\text{chip rate}$). The impulse response of the filter is given as follows:

$$g(t) = B \sqrt{\frac{2\pi}{\ln(2)}} e^{-\left(\frac{2\pi^2 B^2 t^2}{\ln(2)}\right)}$$

31.7 Representation of the modulated waveforms

The modulated PPDU signal is represented as follows:

$$x_{\text{PB}}(t) = \left[A \sum_{n=1}^{N_{\text{PPDU}}} d(n) g(t - nT_{\text{chip}}) \right] \cos(\omega_c t + \phi)$$

where

- $d(n) \in \{-1, 0, 1\}$ are the chips of the PPDU
- T_{chip} is the chip duration
- N_{PPDU} is the number of chips in the processed PPDU
- $g(t)$ is the output of the pulse shaping described in 31.6
- ω_c is the angular frequency of the carrier
- $\phi \in [0, 2\pi]$ is the random phase

31.8 RF requirements

31.8.1 Transmit PSD mask

When operating in the 2450 MHz band, transmit spectral components shall conform to the limits specified in Table 31-13, when measured using a 100 kHz resolution bandwidth.

Table 31-13—Transmit PSD limits in 2450 MHz band

Frequency range	Relative limit	Absolute limit
$ f-f_c > 3.5 \text{ MHz}$	-20 dB	-30 dBm

For the relative limit, the reference level shall be the highest average spectral power measured within ± 1 Hz of the carrier frequency.

When operating in 780 MHz, 863 MHz, and 915 MHz bands, transmit spectral components shall conform to the limits specified in Table 31-14, measured using a 100 kHz resolution bandwidth.

Table 31-14—Transmit PSD limits in 780 MHz, 863 MHz, and 915 MHz bands

Frequency range	Relative limit	Absolute limit
$ f-f_c > 1.2 \text{ MHz}$	-20 dB	-20 dBm

For the relative limit, the reference level shall be the highest average spectral power measured within $\pm 600 \text{ kHz}$ of the carrier frequency.

When operating in 433 MHz and 470 MHz bands, transmit spectral components shall conform to the limits specified in Table 31-15, measured using a 100 kHz resolution bandwidth.

Table 31-15—Transmit PSD limits in 433 MHz and 470 MHz bands

Frequency range	Relative limit	Absolute limit
$ f-f_c > 1.25 \text{ MHz}$	-20 dB	-20 dBm

For the relative limit, the reference level shall be the highest average spectral power measured within $\pm 600 \text{ kHz}$ of the carrier frequency.

31.8.2 Receiver sensitivity

Under the conditions specified in 11.1.8, a compliant device shall be capable of achieving a receiver sensitivity of -85 dBm or better for the modulation format corresponding to the lowest data rate in the given operating band.

31.8.3 Interference rejection capability

The receiver interference rejection capability of the TASK PHY shall be measured as described in 13.3.5. The values for adjacent channel rejection capability and alternate channel rejection capability shall conform to the limits specified in Table 31-16.

Table 31-16—Receiver interference rejection requirements in all the operating bands

Adjacent channel rejection	Alternate channel rejection
0 dB	20 dB

The adjacent channel rejection shall be measured as follows: The desired signal shall be a compliant TASK PHY signal that consists of pseudo-random bits, modulated by any one of the modulation formats defined in Table 31-9, Table 31-10, Table 31-11, and Table 31-12. Either in the adjacent channel or in the alternate channel, the interfering signal shall be generated by a compliant TASK PHY signal employing the same modulation format as that of the desired signal.

The desired signal is input to the receiver at a level of 3 dB greater than the maximum allowed receiver sensitivity specified in 31.8.2. The interfering signal is generated at a level as specified in Table 31-16 relative to the desired signal power. The test shall be performed for only one interfering signal at a time.

The receiver shall meet the PER criterion of 1% at 20 octets of PSDU.

31.8.4 TX-to-RX turnaround time

The TASK PHY shall have a TX-to-RX turnaround time as defined in 11.2.2.

31.8.5 RX-to-TX turnaround time

The TASK PHY shall have an RX-to-TX turnaround time as defined in 11.2.3.

31.8.6 EVM

EVM shall be measured as described in 11.2.4. The TASK PHY shall have EVM values of less than 35%.

31.8.7 Transmit power

The TASK PHY compliant transmitter shall be able to transmit at a power level of at least –13 dBm.

31.8.8 Transmit center frequency tolerance

The TASK PHY transmit center frequency tolerance shall be $\pm 40 \times 10^{-6}$ maximum.

31.8.9 Receiver maximum input level of desired signal

The receiver maximum input level is the maximum power level of the desired signal present at the input of receiver for which the error criterion of 1% PER at 20 octets of PSDU is met. The TASK PHY shall have a receiver maximum input level greater than or equal to –20 dBm.

31.8.10 Receiver ED

The TASK PHY shall provide the ED measurement as described in 11.2.6. The ED measurement time, to average over, shall be equal to 128 chip durations.

31.8.11 SNR measurement

The minimum and maximum SNR values (0x00 and 0xff) should be associated with the lowest and highest quality compliant signals detectable by the receivers, respectively. SNR values in between should be uniformly distributed between these two limits.

31.8.12 CCA

The TASK PHY shall use one of CCA mode 1, CCA mode 2, or CCA mode 3, as described in 11.2.8.

32. RS-GFSK PHY

32.1 PPDU format

32.1.1 General

The SHR, PHR, and PHY payload components are treated as bit strings of length n , numbered b0 on the left and b($n - 1$) on the right. When transmitted, they are processed b0 first to b($n - 1$) last, regardless of their content or structure.

The RS-GFSK PPDU shall be formatted as illustrated in Figure 13-1 for transmissions using the SFD for uncoded or the SFD for FEC coded, as described in 32.1.3.

32.1.2 Preamble field

The Preamble field shall contain $\text{phyRsGfskPreambleLength}$ (as defined in 12.3.9) multiples of the 8-bit sequence “01010101”.

32.1.3 SFD

The SFD shall be selected from the list of values shown in Table 32-1. Devices that do not support any FEC shall support the SFD associated with uncoded (PHR + PSDU). Devices that support the convolutional FEC shall support the SFD for FEC coded (PHR + PSDU) in addition to the SFD for uncoded (PHR + PSDU). If interoperation with SUN FSK PHY is desired, a value of zero for the PIB attribute phyRsGfskSfd may be used. If interoperation with SUN FSK PHY is not desired, a value of one for the PIB attribute phyRsGfskSfd may be used.

Table 32-1—RS-GFSK PHY SFD values for 2-GFSK

	SFD for coded (b0–b15)	SFD for uncoded (b0–b15)
$\text{phyRsGfskSfd} = 0$	0110 1111 0100 1110	1001 0000 0100 1110
$\text{phyRsGfskSfd} = 1$	0011 0101 1100 0110	1001 1010 1111 0000

NOTE—When transmission is in MCS modes 5, 6, and 7 with differential encoding described in 32.2.3, the expected pattern for the SFD on the receiver side will differ from the values shown in Table 32-1.

32.1.4 Long PHR

All RS-GFSK devices shall support the long PHR. The format of the long PHR is shown in Figure 32-1.

Bits: 0	1	2	3	4	5–15
Reserved	Rate Switch	Short PHR	FCS Type	Data Whitening	Frame Length

Figure 32-1—Format of the long PHR for RS-GFSK

Bit 0 is reserved.

The Rate Switch field indicates whether rate switch is enabled or disabled. The Rate Switch field shall be set to one when rate switch is enabled and shall be set to zero otherwise. The rate switch mode is described in 32.3. The rate switch shall be disabled when FEC is used.

The Short PHR field shall be set to zero to indicate the use of the long PHR.

The FCS Type field indicates the length of the FCS field described in 7.2.11 that is included in the MPDU. The transmitted FCS Type field shall be set to zero for a 4-octet FCS and shall be set to one for a 2-octet FCS. When FEC is being used, the transmitted FCS Type field shall be set to zero, and a 4-octet FCS shall be used.

The Data Whitening field indicates whether data whitening is used during transmission. An RS-GFSK device shall have data whitening enabled for all frame transmissions with the Data Whitening field in the PHR set to one.

NOTE—This requirement allows for compatibility with the SUN FSK PHY.

The Frame Length field is an unsigned integer that shall be set to the total number of octets contained in the PSDU (prior to FEC encoding, if enabled). The Frame Length field shall be transmitted MSB first.

32.1.5 Short PHR

Support for the Short PHR is optional. The format of the short PHR is shown in Figure 32-2.

Bits: 0	1	2	3–7
Reserved	Rate Switch	Short PHR	Frame Length

Figure 32-2—Format of the short PHR for RS-GFSK

Bit 0 is reserved.

The Rate Switch field indicates whether rate switch is enabled or disabled. The Rate Switch field shall be set to one when rate switch is enabled and shall be set to zero otherwise. The rate switch mode is described in 32.3.

The Short PHR field shall be set to one to indicate the use of the short PHR. The short PHR format shall not be used when FEC is used.

When the short PHR is used, the length of the FCS field described in 7.2.11 shall be 2 octets.

The Frame Length field is an unsigned integer that shall be set to the total number of octets contained in the PSDU. The Frame Length field shall be transmitted MSB first.

The short PHR may be enabled from a higher layer using the PHY PIB attribute *phyRsGfskShortPhrEnabled*. When this attribute is TRUE, the PSDU length shall be 31 octets or less, and FEC shall be disabled.

NOTE—When the short PHR is used, the maximum PSDU size is limited to 31 octets.

32.2 Modulation and coding

32.2.1 General

The modulation for the RS-GFSK is either a 2-level or a 4-level GFSK with a BT value of 0.5.

The symbol rate and the outer deviation shall be the same across the entire PPDU. When the Rate Switch bit is set to zero, the entire PPDU shall be transmitted using 2-GFSK modulation, i.e., one of the operating modes in Table 32-2. In addition, when the Rate Switch bit is set to zero, the outer deviation shall be determined by the multiplication of the modulation index, as specified in Table 32-2, by half the symbol rate.

Table 32-2—RS-GFSK 2-GFSK MCS

RS-GFSK MCS mode	Data rate (kb/s)	Symbol rate (kb/s)	Channel spacing (kHz)	Modulation index
0	4.8	4.8	12.5	0.76
1	9.6	9.6	25	0.76
2	50	50	200	0.76
3	150	150	400	0.76
4	500	500	1000	0.76
5	250	250	500	0.5
6	500	500	1000	0.5
7	1000	1000	2000	0.5

When the Rate Switch bit is set to one, the SHR and PHR shall be transmitted in 2-GFSK, and the PSDU shall be transmitted in 4-GFSK, i.e., one of the operating modes in Table 32-3. In addition, when the Rate Switch bit is set to one, the outer deviation across the entire PPDU shall be equal to the modulation index, as specified in Table 32-3, multiplied by 1.5 times the symbol rate. In 2-GFSK mode, the symbol rate is equal to the data rate. In 4-GFSK mode, the symbol rate is equal to the data rate divided by 2.

Table 32-3—RS-GFSK 4-GFSK MCS

RS-GFSK operating mode	Data rate (kb/s)	Symbol rate (kb/s)	Channel spacing (kHz)	Modulation index
0a	9.6	4.8	12.5	0.3
1a	19.2	9.6	25	0.3
2a	100	50	200	0.3
3a	300	150	400	0.3
4a	1000	500	1000	0.3

Table 32-2 shows the primary modulation and channel parameters for the RS-GFSK PHY MCSs. The values presented in RS-GFSK MCS mode column correspond to the DataRate as used in MCPS-DATA

primitive as described in 8.3.4. When FEC is enabled, the effective data rate is half of the value that is shown in Table 32-2, due to the rate 1/2 convolutional coding as described in 32.2.8.

Table 32-3 shows the rate switch modulation and channel parameters, which are used in rate switch mode for transmitting the PSDU. The symbol period is defined as the reciprocal value of the symbol rate. If MCS levels with different symbol periods are employed for uplink and downlink, all calculations depending on symbol period shall use the longer symbol period.

32.2.2 Reference modulator diagram

The functional block diagram in Figure 32-3 is provided as a reference for specifying the RS-GFSK PHY data flow processing functions. Each bit shall be processed using the bit order rules defined in 32.1.

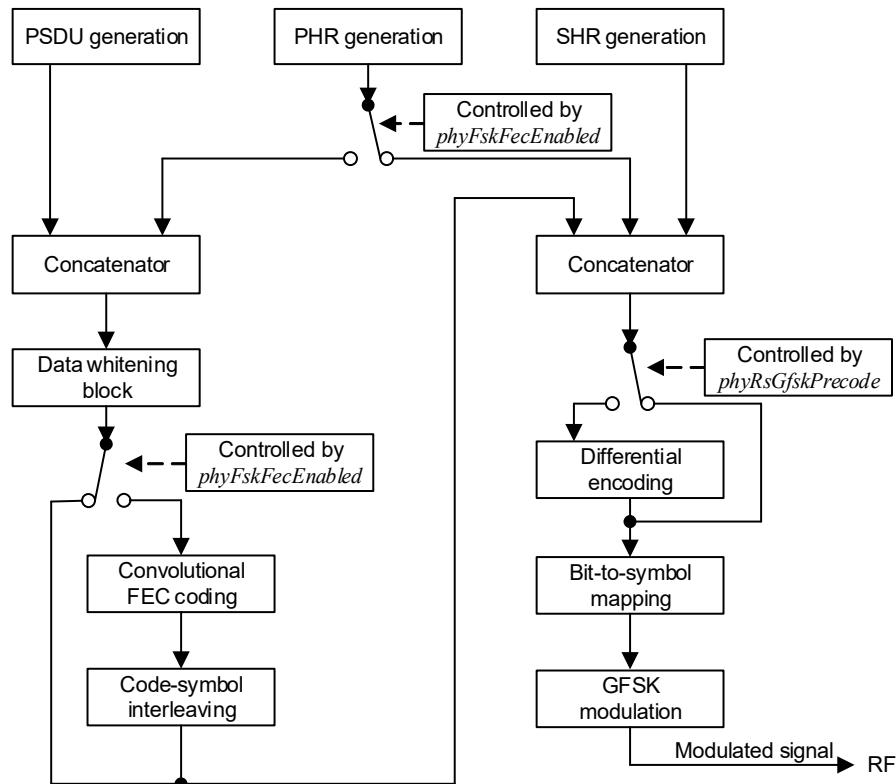


Figure 32-3—RS-GFSK reference modulator diagram

When FEC is enabled, the PHR and PSDU shall be processed for coding, as described in 32.2.8. Differential encoding shall be applied to PHR and PSDU as described in 32.2.3 when MCS mode 5, 6, or 7 is used.

When FEC is not used, data whitening shall be applied over the PSDU, as described in 32.2.10. When FEC is used, data whitening shall be applied over the PHR and the PSDU.

When differential encoding is enabled, the PPDU shall be processed as described in 32.2.3.

32.2.3 Differential encoding

Differential encoding shall be applied for MCS modes 5, 6, and 7 when *phyFskFecEnabled* is TRUE and shall be disabled otherwise.

The procedure of differential encoding shall be employed as described in 14.2.4.

32.2.4 Bit-to-symbol mapping

Bit-to-symbol mapping of the 2-GFSK and 4-GFSK modes shall be the same as the respective 2-FSK and 4-FSK modes as described in 20.3.3.

32.2.5 Modulation quality

Modulation quality shall be measured by observing the frequency deviation tolerance and the zero crossing tolerance of the eye diagram caused by a PN9 sequence of length 511 bits.

32.2.6 Frequency deviation tolerance

The frequency deviation tolerance for 2-GFSK shall be as given in 20.3.4.2. The frequency deviation tolerance for 4-GFSK shall be as given in Figure 32-4.

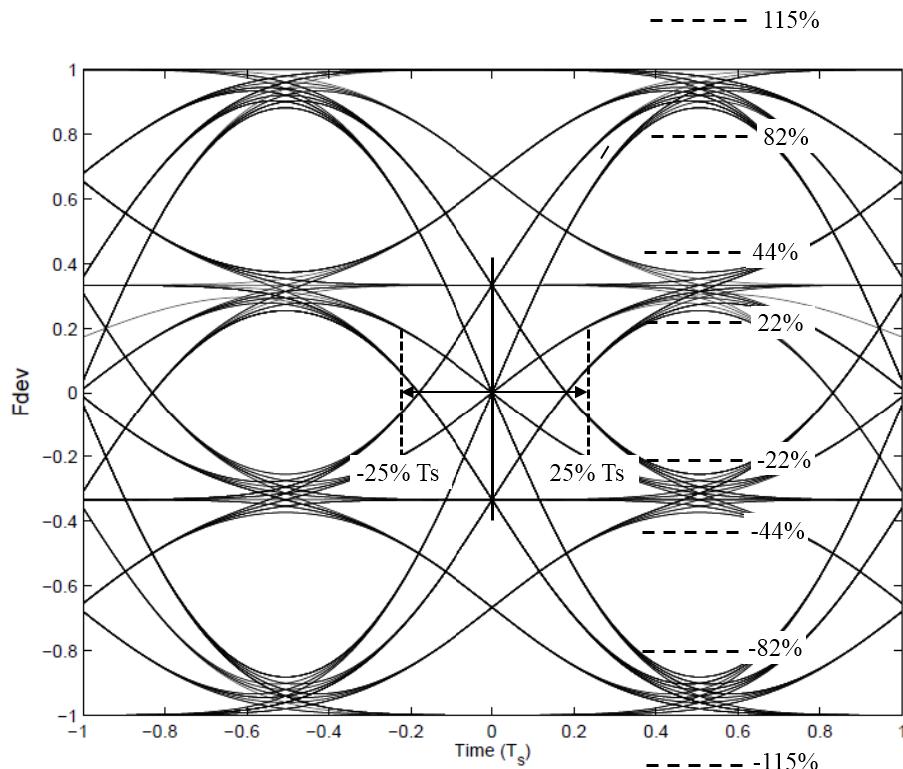


Figure 32-4—Eye diagram of 4GFSK modulation

F_{dev} is the normalized frequency deviation.

$$F_{\text{dev}} = \frac{2F(t)}{3h \times R_s}$$

where

$F(t)$ is the measured frequency

- h is the modulation index
- R_s is the symbol rate as defined in Table 32-3

The symbol timing accuracy shall be the same or better than the radio frequency tolerance as specified in 32.4.1.

32.2.7 Zero crossing tolerance

The zero crossing tolerance for 2-GFSK shall be as given in 20.3.4.3. The frequency crossing tolerance for 4-GFSK shall be set as in Figure 32-4.

32.2.8 FEC

FEC is optional. If *phyFskFecEnabled* indicates the usage of convolutional FEC code, it shall be applied as described in 24.4.5 with the following changes:

Prior to the convolutional encoding of the PHR and PSDU bits, the initial encoder state at $k = 0$ shall be set as follows:

$$(u_{-1}, u_{-2}, \dots, u_{-6}) = (0, 0, 0, 0, 0, 0)$$

The pad bits shall be set to zero; and the number of pad bits, N_{PAD} , is computed from the number of blocks, N_B , and the total number of uncoded bits, N_D , as follows:

$$N_B = \text{ceiling}((8 \times \text{LENGTH} + 6)/16)$$

$$N_D = N_B \times 16$$

$$N_{\text{PAD}} = N_D - (8 \times \text{LENGTH} + 6)$$

Instead of using the sequence shown in Figure 24-12, the sequence shown in Figure 32-5 shall be passed to the convolutional encoder.

PHR bits	PSDU bits	000000	pad bits
----------	-----------	--------	----------

Figure 32-5—PSDU extension prior to encoding

32.2.9 Code-symbol interleaving

When FEC is used, interleaving of code bits shall be employed, as described in 20.3.6. No interleaving shall be employed if FEC is not enabled.

32.2.10 Data whitening for RS-GFSK

Data whitening is mandatory for all frame transmissions.

The procedure of data whitening shall be employed as described in 17.2.3.

32.3 Rate switch RS-GFSK

The Rate Switch field in the PHR shall be set to one when rate switch is enabled and shall be set to zero otherwise. Enabling rate switch is optional. When rate switch is enabled, the SHR and the PHR shall be transmitted using any 2-GFSK MCS with modulation index 0.9, and the PSDU shall be transmitted using the same symbol rate as used during the SHR and PHR, but employing a 4-GFSK operation mode with modulation index 0.3. When rate switch is disabled, a single MCS is used during the transmission of the PPDU. The capability of receiving and transmitting frames with rate switch enabled may be communicated by setting the Rate Switch field in the RS-GFSK Device Capabilities IE to one. Then, the device shall be responsive to both states of the received Rate Switch bit in the PHR. Also, the device shall be capable of transmitting frames with rate switch enabled and disabled.

32.4 RF requirements

32.4.1 RF tolerance

The single-sided clock frequency tolerance T at the transmitter, in 10^{-6} , shall be as follows:

$$T \leq \min\left(\frac{T_0 \times R \times h \times F_0}{R_0 \times h_0 \times F}, 30\right)$$

for all combinations of R , h , and F and for each mode supported by the device, where

- R is the symbol rate, in ksymbol/s
- h is the modulation index used for the 2GFSK part of the frame
- F is the carrier frequency, in MHz
- R_0 is 50 ksymbol/s
- h_0 is 0.76
- F_0 is 915 MHz
- T_0 is 20×10^{-6} for modes in all bands, except at 2450 MHz for which the value of T_0 is 40×10^{-6}

32.4.2 Channel switch time

Channel switch time shall be less than or equal to 500 μ s. The channel switch time is defined as the time elapsed at the antenna between the trailing edge of the last symbol of one PPDU to the leading edge of the first symbol of a consecutive PPDU sent on a different channel.

32.4.3 Receiver sensitivity

Under the conditions specified in 11.1.8, the RS-GFSK receiver sensitivity shall be better than S , where S is defined, in dBm, as follows:

$$S = \min\left(S_0 + 10 \log_{10}\left(\frac{R}{R_0}\right), -85\right)$$

where

- S_0 is taken from Table 32-4
- R_0 is 50 kb/s
- R is the bit rate, in kb/s

Table 32-4— S_0 values for receiver sensitivity

	Uncoded	FEC
Without differential encoding	-91	-99
With differential encoding	N/A	-102

32.4.4 Receiver interference rejection

The receiver interference rejection shall be measured as described in 20.6.8.

32.4.5 TX-to-RX turnaround time

The RS-GFSK PHY shall have a TX-to-RX turnaround time as defined in 11.2.2.

32.4.6 RX-to-TX turnaround time

The RS-GFSK PHY shall have an RX-to-TX turnaround time as defined in 11.2.3.

32.4.7 Receiver maximum input level of desired signal

The RS-GFSK PHY shall have a receiver maximum input level greater than or equal to -20 dBm using the measurement defined in 11.2.5.

32.4.8 Receiver ED

The RS-GFSK PHY shall provide the receiver ED measurement as described in 11.2.6.

32.4.9 LQI

The RS-GFSK PHY shall provide the LQI measurement as described in 11.2.7.

32.4.10 CCA

The RS-GFSK PHY shall use one of CCA mode 1, CCA mode 2, CCA mode 3, or CCA mode 4, as described in 11.2.8.

Annex A

(informative)

Bibliography

Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this standard. Reference to these resources is made for informational use only.

- [B1] "15.4z HRP UWB PHY Test Vectors," IEEE 802.15 document 15-20-0002-01-004z, 2020.²⁵
- [B2] "802.15.4 ANA database," IEEE 802.15 document 15-13-0257, 2015.
- [B3] ANSI X9.63-2001, Public Key Cryptography for the Financial Services Industry—Key Agreement and Key Transport Using Elliptic Curve Cryptography.²⁶
- [B4] "Application of IEEE Std 802.15.4," IEEE 802.15 document 15-14-0226-01-0000, 2014.
- [B5] ARIB STD-T108, 920MHz-Band Telemeter, Telecontrol and Data Transmission Radio Equipment.²⁷
- [B6] Capkun, S., D. Basin, and B. Danev, "Authenticated Ranging of IEEE 802.15.4," IEEE 802.15 document 15-19-0423-00-0000, 2019.
- [B7] Chang, S.-Y. and C. Seibert, "TG 15.4m Coexistence Assurance Document (CAD)," IEEE 802.15 document 15-13-0166-03-004m, 2013.
- [B8] "Coexistence analysis of IEEE Std 802.15.4 with other IEEE standards and proposed standards," IEEE 802.15 document 15-10-0808-00-0000, 2010.
- [B9] "Coexistence Document for IEEE 802.15.4z", IEEE 802.15 document 15-18-0523-06-004z, 2018.
- [B10] "Examples of 802.15.4 PHY encodings," IEEE 802.15 document 15-14-0225-00-0000, 2014.
- [B11] IEEE 802.15 Operations Manual, IEEE 802.15 document 15-10-0235 latest version.
- [B12] "IEEE 802.15.4aa Coexistence Assessment Document," IEEE 802.15 document 15-21-0083-08-04aa, 2021
- [B13] IEEE Std 802.11™, IEEE Standard for Information Technology—Telecommunications and Information Exchange between Systems—Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.^{28, 29}
- [B14] IEEE Std 802.15.8™-2017, IEEE Standard for Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Peer Aware Communications (PAC), Annex D, subclause D2.

²⁵ IEEE 802.15 documents are available at <https://mentor.ieee.org/802.15/documents>.

²⁶ ANSI publications are available from the American National Standards Institute (<https://www.ansi.org/>)

²⁷ ARIB publications are available at <https://www.arib.or.jp/english/>.

²⁸ IEEE publications are available from The Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>).

²⁹ The IEEE standards or products referred to in Annex A are trademarks owned by The Institute of Electrical and Electronics Engineers, Incorporated.

- [B15] IETF RFC 3629, UTF-8, a transformation format of ISO 10646, 2003.³⁰
- [B16] IETF RFC 5116, An Interface and Algorithms for Authenticated Encryption, 2008.
- [B17] Jonsson, J., “On the security of CTR + CBC-MAC,” in Proceedings of Selected Areas in Cryptography—SAC 2002, Nyberg, K., Heys, H., eds., lecture notes in *Computer Science*, vol. 2595, pp. 76–93, Berlin: Springer, 2002.
- [B18] Jonsson, J., “On the security of CTR + CBC-MAC, NIST Modes of Operation – Additional CCM Documentation”.
- [B19] Kivinen, T., “AES-256 Test Vectors,” IEEE 802.15 document 15-21-0005-00-004y, 2021.
- [B20] Kivinen, T., “Security Section Pictures,” IEEE 802.15 document 15-15-0106-08-0mag, 2015.
- [B21] Lafer, M. and F. Leong, “Description 15.4z HRP UWB PHY Test Vectors,” IEEE 802.15 document 15-20-0003-02-004z, 2020.
- [B22] Li, L., A. Astrin, A. Bottomley, and K. Mori, “Chinese Radio Regulation Discussion around Chinese MIIT DOC 423-2005,” IEEE 802.15 document 15-13-0313-03-4n, 2013.³¹
- [B23] Li, N., L. Li, T. Shui, L. Zhang, S. Li, and G.-L. Du, “Detail Report for Interference on Chinese Medical Bands,” IEEE 802.15 document 15-12-0471-03-4n, 2014.
- [B24] Lu, L., K. Mizutani, C.-S. Sum, F. Kojima, and H. Harada, “TVWS-NB-OFDM Frame Example,” IEEE 802.15 document 15-13-0565-02-004m, 2013.
- [B25] Nair, J. P., C. Thejaswi, K. Bynam, and H. de Ruijter, “TG4q Coexistence Assurance Document,” IEEE 802.15 document 15-14-0709-00-004q, 2014.
- [B26] NIST SP 800-38C, Recommendation for Block Cipher Modes of Operation—The CCM Mode for Authentication and Confidentiality, U.S. Department of Commerce/NIST, 12 May 2004, updated 20 July 2007.³²
- [B27] NITS/CWPAN Part 15.4, Chinese standard for the Wireless Medium Access Control (MAC) and the Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks, GB/T 15629.15-2010.
- [B28] Powell, C., “TG4t Coexistence Assurance Document,” IEEE 802.15 document 15-16-00408-01-004t, 2016.
- [B29] Rogaway, P. and D. Wagner, “A critique of CCM,” IACR ePrint Archive 2003-070, 13 Apr. 2003.³³
- [B30] Seibert, C., “Example of encoding a packet for the TVWS-FSK PHY,” IEEE 802.15 document 15-13-0131-01-004m, 2013.
- [B31] Shin, C., B.H. Kim, S. Choi, and S.-Y. Chang, “TVWS-OFDM Frame Example,” IEEE 802.15 document 15-13-0287-01-004m, 2013.

³⁰ IETF RFCs are available from the Internet Engineering Task Force (<https://www.ietf.org/>).

³¹ IEEE 802.15 documents are available at <https://mentor.ieee.org/802.15/documents>.

³² NIST publications are available from the National Institute of Standards and Technology (<https://www.nist.gov/>).

³³ Publication is available from <https://www.iacr.org/>.

[B32] “TG4f Coexistence Assurance Document,” IEEE 802.15 document 15-10-0918-01-004f, 2010.

[B33] “TG4w Coexistence Document,” IEEE 802.15 document 15-19-0165-01-004w, 2019.

[B34] “Translation of Chinese MIIT DOC; 423-2005 Technical Requirements for Micro-power (short-distance) Radio Devices,” IEEE 802.15 document 15-12-0105-02-4n, 2013.

[B35] Verso, B. and J. Niewczas, “802.15.4z - HRP UWB PHY - HPRF mode preamble sequence cross-correlation properties,” IEEE 802.15 document 15-21-0152-00-0000, 2021.

Annex B

(normative)

CCM* and CCM mode of operation

B.1 Introduction

Extension of counter mode encryption and cipher block chaining message authentication code (CCM*) and CCM are generic combined encryption, counter mode, and authentication block cipher modes. The CCM* mode coincides with the original specification for the combined counter with cipher block chaining message authentication code (CBC-MAC) (CCM) mode of operation (ANSI X9.63-2001 [B3], Appendix A of NIST SP 800-38C [B26]) for messages that require authentication and, possibly, encryption, but also offers support for messages that require only encryption. Moreover, CCM* can be used in implementation environments for which the use of variable-length authentication tags, rather than fixed-length authentication tags only, is beneficial.

B.2 Symmetric-key cryptographic building blocks

B.2.1 General

The symmetric-key cryptographic primitives and mechanisms are defined for use with all security processing operations specified in this standard. This annex uses the notation, and representation of strings, integers, and octets as described in 9.3.1.

B.2.2 Block cipher

The block cipher used in this annex shall be AES-128 or AES-256, as specified in FIPS Pub 197. The generation of keys is outside the scope of this standard.

B.2.3 Mode of operation

The block cipher mode of operation used shall be the generic CCM* or CCM mode of operation, as specified in B.3, with the following instantiations:

- a) Each entity shall use the block cipher E as specified in B.2.2 with a block size of 128 bits.
- b) All integers shall be represented as octet strings as specified in 9.3.1.
- c) All octets shall be represented as binary strings as specified in 9.3.1.
- d) The parameter L shall have the integer value 2.
- e) The parameter M shall have one of the following integer values: 4, 8, or 16.

B.3 Specification of generic CCM* and CCM modes of operation

B.3.1 Prerequisites

The following are the prerequisites for the operation of the generic CCM* or CCM modes:

- a) A block cipher encryption function E was chosen, with a 128-bit block size. The length in bits of the keys used by the chosen encryption function is denoted by keylen.
- b) A fixed representation of integers as octet strings was chosen (e.g., most-significant-octet-first order or least-significant-octet-first order).
- c) A fixed representation of octets as binary strings was chosen (e.g., most-significant-bit-first order or least-significant-bit-first order).
- d) The length L of the message Length field, in octets, was chosen. Valid values for L are the integers 2, 3, ..., 8 (the value $L = 1$ is reserved).
- e) The length M of the Authentication field, in octets, was chosen. Valid values for M are the integers 4, 6, 8, 10, 12, 14, and 16.

B.3.2 CCM* and CCM modes encryption and authentication transformation

B.3.2.1 Inputs

The CCM* and CCM mode forward transformations take the following as inputs:

- a) A bit string Key of length keylen bits to be used as the key. Each entity shall have evidence that access to this key is restricted to the entity itself and its intended key sharing group member(s).
- b) A nonce N of $15 - L$ octets. Within the scope of any encryption key Key, the nonce value shall be unique.
- c) An octet string m of length $l(m)$ octets, where $0 \leq l(m) < 2^{8L}$.
- d) An octet string a of length $l(a)$ octets, where $0 \leq l(a) < 2^{64}$.

When TSCH mode is not enabled, the nonce N shall encode the potential values for M so that the actual value of M can be uniquely determined from N . When TSCH mode is enabled, the nonce generation does not include the value of M , meaning using the same key with different values of M might not be secure.

B.3.2.2 Actions

The CCM* and CCM mode forward transformations involve the execution, in order, of an input transformation, as defined in B.3.2.3, an authentication transformation, as defined in B.3.2.4, and an encryption transformation, as defined in B.3.2.5.

B.3.2.3 Input transformation

This step involves the transformation of the input strings a and m to the strings AuthData and PlaintextData, to be used by the authentication transformation and the encryption transformation, respectively.

This step involves the following steps, in order:

- a) Form the octet string representation $L(a)$ of the length $l(a)$ of the octet string a , as follows:
 - 1) If $l(a) = 0$, then $L(a)$ is the empty string.
 - 2) If $0 < l(a) < 2^{16} - 2^8$, then $L(a)$ is the 2-octet encoding of $l(a)$.

- 3) If $2^{16} - 2^8 \leq l(a) < 2^{32}$, then $L(a)$ is the right-concatenation of the octet 0xff, the octet 0xfe, and the 4-octet encoding of $l(a)$.
- 4) If $2^{32} \leq l(a) < 2^{64}$, then $L(a)$ is the right-concatenation of the octet 0xff, the octet 0xff, and the 8-octet encoding of $l(a)$.
- b) Right-concatenate the octet string $L(a)$ with the octet string a itself. Note that the resulting string contains $l(a)$ and a encoded in a reversible manner.
- c) Form the padded message AddAuthData by right-concatenating the resulting string with the smallest non-negative number of all-zero octets so that the octet string AddAuthData has length divisible by 16.
- d) Form the padded message PlaintextData by right-concatenating the octet string m with the smallest non-negative number of all-zero octets so that the octet string PlaintextData has length divisible by 16.
- e) Form the message AuthData consisting of the octet strings AddAuthData and PlaintextData:

$$\text{AuthData} = \text{AddAuthData} \parallel \text{PlaintextData}.$$

B.3.2.4 Authentication transformation

The data AuthData that was established in B.3.2.3 shall be tagged using the tagging transformation as follows:

- a) Form the 1-octet Flags field consisting of the 1-bit Reserved field, the 1-bit Adata field, and particular 3-bit representations of the integers M and L , as follows:

$$\text{Flags} = \text{Reserved} \parallel \text{Adata} \parallel M \parallel L$$

 Here, the 1-bit Reserved field is reserved for future expansions and shall be set to zero. The 1-bit Adata field is set to zero if $l(a) = 0$ and set to one if $l(a) > 0$. The M field is the 3-bit representation of the integer $(M - 2)/2$ in most-significant-bit-first order. The L field is the 3-bit representation of the integer $L - 1$, in most-significant-bit-first order.
- b) Form the 16-octet B_0 field consisting of the 1-octet Flags field defined in step a) in this subclause, the $(15 - L)$ -octet Nonce field N , and the L -octet representation of the Length field $l(m)$, as follows:

$$B_0 = \text{Flags} \parallel \text{Nonce } N \parallel l(m)$$
- c) Parse the message AuthData as $B_1 \parallel B_2 \parallel \dots \parallel B_t$, where each message block B_i is a 16-octet string.
- d) The CBC-MAC value X_{t+1} is defined as follows:

$$X_0 := 0^{128}; X_{i+1} := E(\text{Key}, X_i \oplus B_i) \quad \text{for } i = 0, \dots, t.$$

 Here, $E(K, x)$ is the cipher text that results from encryption of the plaintext x , using the established block cipher encryption function E with key K ; the string 0^{128} is the 16-octet all-zero bit string.
- e) The authentication tag T is the result of omitting all but the leftmost M octets of the CBC-MAC value X_{t+1} thus computed.

B.3.2.5 Encryption transformation

The data PlaintextData that was established in B.3.2.3 [step d)] and the authentication tag T that was established in B.3.2.4 [step e)] shall be encrypted using the encryption transformation as follows:

- a) Form the 1-octet Flags field consisting of two 1-bit Reserved fields, and particular 3-bit representations of the integers 0 and L , as follows:

$$\text{Flags} = \text{Reserved} \parallel \text{Reserved} \parallel 0 \parallel L$$

 Here, the two 1-bit Reserved fields are reserved for future expansions and shall be set to ‘0’. The ‘0’ field is the 3-bit representation of the integer 0, in most-significant-bit-first order. The L field is the 3-bit representation of the integer $L - 1$, in most-significant-bit-first order.

- b) Define the 16-octet A_i field consisting of the 1-octet Flags field defined in step a) in this subclause, the $(15 - L)$ -octet Nonce field N , and the L -octet representation of the integer i , as follows:

$$A_i = \text{Flags} \parallel \text{Nonce } N \parallel \text{Counter } i, \text{ for } i = 0, 1, 2, \dots$$
 All the A_i fields are distinct from the B_0 fields that are actually used, as those have a Flags field with a nonzero encoding of M in the positions where all A_i fields have an all-zero encoding of the integer 0, as described in B.3.2.4, step b).
- c) Parse the message PlaintextData as $M_1 \parallel \dots \parallel M_t$, where each message block M_i is a 16-octet string.
- d) The cipher text blocks C_1, \dots, C_t are defined as follows:

$$C_i := E(\text{Key}, A_i) \oplus M_i \text{ for } i = 1, 2, \dots, t$$
- e) The string Ciphertext is the result of omitting all but the leftmost $l(m)$ octets of the string $C_1 \parallel \dots \parallel C_t$
- f) Define the 16-octet encryption block S_0 as follows:

$$S_0 := E(\text{Key}, A_0)$$
- g) The encrypted authentication tag U is the result of XORing the string consisting of the leftmost M octets of S_0 and the authentication tag T .

B.3.2.6 Output

If any of the preceding operations has failed, then output “invalid”. Otherwise, output the right-concatenation c of the encrypted message Ciphertext and the encrypted authentication tag U .

B.3.3 CCM* and CCM modes decryption and authentication checking transformations

B.3.3.1 Inputs

The CCM* and CCM mode inverse transformation takes the following as inputs:

- a) A bit string Key of length keylen bits to be used as the key. Each entity shall have evidence that access to this key is restricted to the entity itself and its intended key-sharing group member(s).
- b) A nonce N of $15 - L$ octets. Within the scope of any encryption key Key, the nonce value shall be unique.
- c) An octet string c of length $l(c)$ octets, where $0 \leq l(c) - M < 2^{8L}$.
- d) An octet string a of length $l(a)$ octets, where $0 \leq l(a) < 2^{64}$.

B.3.3.2 Actions

The CCM* and CCM modes inverse transformations involves the execution, in order, of a decryption transformation, as defined in B.3.3.3, and an authentication checking transformation, as defined in B.3.3.4.

B.3.3.3 Decryption transformation

The decryption transformation involves the following steps, in order:

- a) Parse the message c as $C \parallel U$, where the rightmost string U is an M -octet string. If this operation fails, output “invalid” and stop. U is the purported encrypted authentication tag. Note that the leftmost string C has length $l(c) - M$ octets.
- b) Form the padded message CiphertextData by right-concatenating the string C with the smallest non-negative number of all-zero octets so that the octet string CiphertextData has length divisible by 16.
- c) Use the encryption transformation in B.3.2.5, with as inputs the data CiphertextData and the tag U .

- d) Parse the output string resulting from applying this transformation as $m \parallel T$, where the rightmost string T is an M -octet string. T is the purported authentication tag. Note that the leftmost string m has length $l(c) - M$ octets.

B.3.3.4 Authentication checking transformation

The authentication checking transformation involves the following steps, in order:

- a) Form the message AuthData using the input transformation in B.3.2.3, with as inputs the string a and the octet string m that was established in B.3.3.3 [step d].
- b) Use the authentication transformation in B.3.2.4, with as input the message AuthData.
- c) Compare the output tag MACTag resulting from this transformation with the tag T that was established in B.3.3.3 [step d]. If $MACTag = T$, output “valid”; otherwise, output “invalid” and stop.

B.3.3.5 Output

If any of the preceding verifications has failed, then output “invalid”, and reject the octet strings a and m . Otherwise, accept the octet strings a and m , and accept one of the key sharing group member(s) as the source of a and m .

B.3.4 Restrictions

All implementations shall limit the total amount of data that is encrypted with a single key. The CCM* and CCM encryption and authentication transformations shall invoke not more than 2^{61} block cipher encryption function invocations with the same key in total.

The CCM* and CCM decryption and authentication checking transformations shall not expose any information if any verification check fails. The only information that may be exposed in this case is that the authenticity verification transformation failed; all other information, such as the purported plaintext, shall be destroyed.

NOTE 1—With regard to security of the CCM* mode of operation, the CCM* mode coincides with the original CCM mode specification (ANSI X9.63-2001 [B3]) for messages that require authentication and, possibly, encryption. Moreover, it can be used in implementation environments for which the use of variable-length authentication tags, rather than fixed-length authentication tags only, is beneficial. As with the CCM mode, the CCM* mode requires only one key. The CCM* specification differs from the CCM specification, as follows:

- The CCM* mode imposes a further restriction on the nonce N : it shall encode the potential values for M so that one can uniquely determine from N the actually used value of M .

As a result, if M is fixed and the value $M = 0$ is not allowed, then there are no additional restrictions on N , in which case the CCM* mode reduces to the CCM mode. In particular, the proof of the CCM mode applies (Jonsson [B17] and [B18]).

For fixed-length authentication tags, the CCM* mode is equally secure as the original CCM mode. For variable-length authentication tags, the CCM* mode completely avoids, by design, the vulnerabilities that do apply to the original CCM mode when non-TSCH mode is used. When TSCH mode is used, then devices use fixed-length authentication tags, and variable-length authentication tags are not allowed for same key.

For fixed-length authentication tags, the security proof of the original CCM mode carries over to that of the CCM* mode, by observing that the proof of the original CCM mode relies on the following properties, which slightly relax those stated in Jonsson [B17] and [B18] (relaxed property indicated in italics):

- The B_0 field uniquely determines the value of the nonce N .
- The authentication transformation operates on input strings $B_0 \parallel B_1 \parallel B_2 \parallel \dots \parallel B_t$ from which one can uniquely determine the input strings a and m (as well as the nonce N). In fact, for any two input strings corresponding to distinct triples (N, m, a) , neither one is a prefix string of the other.

- All the A_i fields are distinct from the B_0 fields *that are actually used* (over the lifetime of the key), as those have a Flags field with a nonzero encoding of M in the positions where all A_i fields have an all-zero encoding of the integer 0.

Hence, if M is fixed, then the CCM* mode offers the same security properties as the original CCM mode: confidentiality over the input string m and data authenticity over the input strings a and m , relative to the length of the authentication tag.

For variable-length authentication tags, the original CCM mode is known to be vulnerable to specific attacks (e.g., Section 3.4 of Rogaway and Wagner [B29]). These attacks may arise with the original CCM mode because the decryption transformation does not depend on the length of the authentication tag itself. The CCM* mode avoids these attacks when used in non-TSCH mode by requiring that one shall be able to uniquely determine the length of the applicable authentication tag from the A_i fields (i.e., from the counters blocks).

NOTE 2—With regard to the interoperability between CCM mode and CCM* mode of operation, the CCM* mode reduces to the CCM mode in all implementation environments where the length of the authentication tag is fixed. In particular, the CCM* mode is compatible with the CCM mode, as specified in IEEE Std 802.11™-2007 (for WLANs), IEEE Std 802.15.3™-2003 (for WPANs), and IEEE Std 802.15.4-2003 (for older WPANs).

NOTE 3—Test vectors for cryptographic building blocks are given in Annex C.

Annex C

(informative)

Test vectors for cryptographic building blocks

C.1 General

With regard to the AEAD mode of operation, as described in Annex B, this annex provides sample test vectors for the IEEE 802.15.4 community, aimed at assisting in building interoperable security implementations.

C.2 AES block cipher

FIPS Pub 197 provides sample test vectors for the block cipher specified in B.2.2.

C.3 Mode of operation

C.3.1 General

This subclause provides sample test vectors for the mode of operation as specified in B.2.3, illustrated in the context of different MAC frame types.

C.3.2 MAC beacon frame

C.3.2.1 Description

The example below illustrates security processing of a beacon frame that is transmitted by the coordinator using its extended source address. In this example, the Superframe Specification field is set to 0xCF55 (e.g., the beacon order and superframe order have integer value 5, while the final CAP slot has integer value 15), and there are no pending addresses. This example uses source address 0xACDE480000000001, PAN ID 0x4321, and beacon payload 0x51 0x52 0x53 0x54; the frame counter has integer value 5. The security level is set to 0x02 (MIC-64, or 64-bit data authenticity).

For simplicity, all frames in this example are shown without the FCS field (because security processing is independent of it).

- Secured beacon frame: 08 D0 84 21 43 01 00 00 00 00 48 DE AC || 02 05 00 00 00 || 55 CF 00 00 51 52 53 54 22 3B C1 EC 84 1A B5 53.
- Corresponding unsecured beacon frame: 00 C0 84 21 43 01 00 00 00 00 48 DE AC || 55 CF 00 00 51 52 53 54.
- Prerequisite: For this mode of operation, the parameter M has the integer value eight.

C.3.2.2 AEAD mode encryption and authentication transformation

C.3.2.2.1 Inputs

The inputs to the AEAD mode forward transformation are as follows:

- a) The key Key of size keylen = 128 bits to be used:

Key = C0 C1 C2 C3 C4 C5 C6 C7 C8 C9 CA CB CC CD CE CF

- b) The nonce N of $15 - L = 13$ octets to be used:

Nonce = AC DE 48 00 00 00 00 01 || 00 00 00 05 || 02

- c) The octet string m of length $l(m) = 0$ octets to be used:

$m = (\text{empty string})$

- d) The octet string a of length $l(a) = 26$ octets to be used:

$a = 08\ 00\ 84\ 21\ 43\ 01\ 00\ 00\ 00\ 00\ 48\ DE\ AC\ ||\ 02\ ||\ 05\ 00\ 00\ 00\ ||\ 55\ CF\ 00\ 00\ 51\ 52\ 53\ 54$

C.3.2.2.2 Actions

The AEAD mode forward transformation involves the execution, in order, of an input transformation, as defined in C.3.2.2.3, an authentication transformation, as defined in C.3.2.2.4, and an encryption transformation, as defined in C.3.2.2.5.

C.3.2.2.3 Input transformation

This step involves the transformation of the input strings a and m to the strings AuthData and PlaintextData, to be used by the authentication transformation and the encryption transformation, respectively.

- a) Form the octet string representation $L(a)$ of the length $l(a)$ of the octet string a :

$L(a) = 00\ 1A$

- b) Right-concatenate the octet string $L(a)$ with the octet string a itself:

$L(a) || a = 00\ 1A\ ||\ 08\ 00\ 84\ 21\ 43\ 01\ 00\ 00\ 00\ 00\ 48\ DE\ AC\ 02\ 05\ 00\ 00\ 00\ 55\ CF\ 00\ 00\ 51\ 52\ 53\ 54$

- c) Form the padded message AddAuthData by right-concatenating the resulting string with the smallest non-negative number of all-zero octets so that the octet string AddAuthData has length divisible by 16:

$\text{AddAuthData} = 00\ 1A\ 08\ 00\ 84\ 21\ 43\ 01\ 00\ 00\ 00\ 00\ 48\ DE\ AC\ 02\ 05\ 00\ 00\ 00\ 55\ CF\ 00\ 00\ 51\ 52\ 53\ 54\ 00\ 00\ 00\ 00$

- d) Form the padded message PlaintextData by right-concatenating the octet string m with the smallest non-negative number of all-zero octets so that the octet string PlaintextData has length divisible by 16:

$\text{PlaintextData} = (\text{empty string})$

- e) Form the message AuthData consisting of the octet strings AddAuthData and PlaintextData:

$\text{AuthData} = 00\ 1A\ 08\ 00\ 84\ 21\ 43\ 01\ 00\ 00\ 00\ 00\ 48\ DE\ AC\ 02\ 05\ 00\ 00\ 00\ 55\ CF\ 00\ 00\ 51\ 52\ 53\ 54\ 00\ 00\ 00\ 00$

C.3.2.2.4 Authentication transformation

The data AuthData that was established in C.3.2.2.3 is tagged using the tagging transformation as follows:

- a) Form the 1-octet Flags field:

Flags = 59

- b) Form the 16-octet B_0 field:

$B_0 = 59 \parallel AC\ DE\ 48\ 00\ 00\ 00\ 00\ 01\ 00\ 00\ 00\ 05\ 02 \parallel 00\ 00$

- c) Parse the message AuthData as $B_1 \parallel B_2$, where each message block B_i is a 16-octet string.
- d) The CBC-MAC value X_3 is computed as shown in Table C.1.

Table C.1—Computation of CBC-MAC value

i	B_i	X_i
0	59 AC DE 48 00 00 00 00 01 00 00 00 00 05 02 00 00	00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
1	00 1A 08 D0 84 21 43 01 00 00 00 00 48 DE AC 02	C4 A4 D0 BD 70 73 7E 32 11 2E 51 9A CA A2 01 F1
2	05 00 00 00 55 CF 00 00 51 52 53 54 00 00 00 00	A9 70 2C 6E E1 7E DE E0 C7 32 88 0A 40 41 7F 9C
3	—	AB 6B 19 E7 5B 75 2D 9A 6E F0 CC 13 09 98 EB D0

- e) The authentication tag T is the result of omitting all but the leftmost $M = 8$ octets of the CBC-MAC value X_3 :

$T = AB\ 6B\ 19\ E7\ 5B\ 75\ 2D\ 9A$

C.3.2.2.5 Encryption transformation

The data PlaintextData that was established in C.3.2.2.3 [step d)] and the authentication tag T that was established in C.3.2.2.4 [step e)] are encrypted using the encryption transformation as follows:

- a) Form the 1-octet Flags field:

Flags = 01

- b) Define the 16-octet A_i field as shown in Table C.2.

Table C.2— A_i fields

i	A_i
0	01 AC DE 48 00 00 00 00 01 00 00 00 00 05 02 00 00

- c) Define the 16-octet encryption block S_0 :

$S_0 := E(\text{Key}, A_0) = 89\ 50\ D8\ 0B\ DF\ 6F\ 98\ C9\ 63\ F2\ D5\ A1\ 08\ A1\ 55\ C7$

- d) The encrypted authentication tag U is the result of XORing the string consisting of the leftmost $M = 8$ octets of S_0 and the authentication tag T :

$U = 22\ 3B\ C1\ EC\ 84\ 1A\ B5\ 53$

C.3.2.2.6 Output

The octet string $c = 22\ 3B\ C1\ EC\ 84\ 1A\ B5\ 53$.

C.3.2.3 AEAD mode decryption and authentication checking transformation

C.3.2.3.1 Inputs

The inputs to the AEAD mode inverse transformation are as follows:

- a) The key Key of size keylen = 128 bits to be used:

Key = C0 C1 C2 C3 C4 C5 C6 C7 C8 C9 CA CB CC CD CE CF

- b) The nonce N of $15 - L = 13$ octets to be used:

Nonce = AC DE 48 00 00 00 00 01 || 00 00 00 05 || 02

- c) The octet string c of length $l(c) = 8$ octets to be used:

$c = 22\ 3B\ C1\ EC\ 84\ 1A\ B5\ 53$

- d) The octet string a of length $l(a) = 26$ octets to be used:

$a = 08\ D0\ 84\ 21\ 43\ 01\ 00\ 00\ 00\ 00\ 48\ DE\ AC\ ||\ 02\ ||\ 05\ 00\ 00\ 00\ ||\ 55\ CF\ 00\ 00\ 51\ 52\ 53\ 54$

C.3.2.3.2 Actions

The AEAD mode inverse transformation involves the execution, in order, of a decryption transformation, as defined in C.3.2.3.3, and an authentication checking transformation, as defined in C.3.2.3.4.

C.3.2.3.3 Decryption transformation

The decryption transformation involves the following steps, in order:

- a) Parse the message c as $C || U$, where the rightmost string U is an 8-octet string:

$C = \text{(empty string)}$

$U = 22\ 3B\ C1\ EC\ 84\ 1A\ B5\ 53$

- b) Form the 1-octet Flags field:

Flags = 01

- c) Define the 16-octet A_i field as shown in Table C.3.

Table C.3— A_i fields

i	A_i
0	01 AC DE 48 00 00 00 00 01 00 00 00 05 02 00 00

- d) Define the 16-octet encryption block S_0 :

$S_0 = E(\text{Key}, A_0) = 89\ 50\ D8\ 0B\ DF\ 6F\ 98\ C9\ 63\ F2\ D5\ A1\ 08\ A1\ 55\ C7$

- e) The purported authentication tag T is the result of XORing the string consisting of the leftmost $M = 8$ octets of S_0 and the octet string U :

$T = AB\ 6B\ 19\ E7\ 5B\ 75\ 2D\ 9A$

C.3.2.3.4 Authentication checking transformation

The authentication checking transformation involves the following steps, in order:

- a) Form the message AuthData using the input transformation in C.3.2.2.3, with as inputs the string a and the octet string m = (empty string):

AuthData = 00 1A 08 D0 84 21 43 01 00 00 00 00 48 DE AC 02 05 00 00 00 55 CF
00 00 51 52 53 54 00 00 00 00

- b) Use the authentication transformation in C.3.2.2.4, with as input the message AuthData to compute the authentication tag MACTag:

MACTag = AB 6B 19 E7 5B 75 2D 9A

- c) Compare the output tag MACTag resulting from this transformation with the tag T that was established in C.3.2.3.3 [step e]):

$T = AB\ 6B\ 19\ E7\ 5B\ 75\ 2D\ 9A = MACTag$

C.3.2.3.5 Output

Because $MACTag = T$, output “valid”, accept the octet strings a and m , and accept one of the key sharing group member(s) as the source of a and m .

C.3.3 MAC command

C.3.3.1 Description

This example uses frame version 0b01 MAC Command frames. The processing rules for frame version 0b10 MAC Commands is different. In frame version 0b01, the MAC command (first byte after MHR) is not encrypted. In frame version 0b10 MAC Command frames, everything after MHR is encrypted if security level is greater than four.

The example below illustrates security processing of an Association Request command that is transmitted by a device using extended addresses, with acknowledgment enabled. In this example, the Capability field is set to 0xCE. This example uses source address 0xACDE480000000001, destination address 0xACDE480000000002, PAN ID 0x4321, and command payload 0xCE; the frame counter has integer value five. The security level is set to 0x06 (ENC-MIC-64, or data confidentiality with 64-bit data authenticity).

For simplicity, all frames in this example are shown without the FCS field (because security processing is independent of it).

- Secured MAC command: 2B DC 84 21 43 02 00 00 00 00 48 DE AC FF FF 01 00 00 00 00 48 DE AC || 06 05 00 00 00 || 01 D8 4F DE 52 90 61 F9 C6 F1.
- Corresponding unsecured MAC command: 23 CC 84 21 43 02 00 00 00 00 48 DE AC FF FF 01 00 00 00 48 DE AC || 01 CE.
- Prerequisite: For this mode of operation the parameter M has the integer value eight.

C.3.3.2 AEAD mode encryption and authentication transformation

C.3.3.2.1 Inputs

The inputs to the AEAD mode forward transformation are as follows:

- a) The key Key of size keylen = 128 bits to be used:

Key = C0 C1 C2 C3 C4 C5 C6 C7 C8 C9 CA CB CC CD CE CF

- b) The nonce N of $15 - L = 13$ octets to be used:

Nonce = AC DE 48 00 00 00 00 01 || 00 00 00 05 || 06

- c) The octet string m of length $l(m) = 1$ octets to be used:

$$m = \text{CE}$$

- d) The octet string a of length $l(a) = 29$ octets to be used:

$a = 2B\ DC\ 84\ 21\ 43\ 02\ 00\ 00\ 00\ 00\ 48\ DE\ AC\ FF\ FF\ 01\ 00\ 00\ 00\ 00\ 48\ DE\ AC\ ||\ 06\ ||$
 $05\ 00\ 00\ 00\ 00\ ||\ 01$

C.3.3.2.2 Actions

The AEAD mode forward transformation involves the execution, in order, of an input transformation, as defined in C.3.3.2.3, an authentication transformation, as defined in C.3.3.2.4, and an encryption transformation, as defined in C.3.3.2.5.

C.3.3.2.3 Input transformation

This step involves the transformation of the input strings a and m to the strings AuthData and PlaintextData, to be used by the authentication transformation and the encryption transformation, respectively.

- a) Form the octet string representation $L(a)$ of the length $l(a)$ of the octet string a :

$L(a) = 00 \text{ 1D}$

- b) Right-concatenate the octet string $L(a)$ and the octet string a itself:

*L(a) || a = 00 1D || 2B DC 84 21 43 02 00 00 00 00 48 DE AC FF FF
01 00 00 00 00 48 DE AC 06 05 00 00 00 01*

- c) Form the padded message AddAuthData by right-concatenating the resulting string with the smallest non-negative number of all-zero octets so that the octet string AddAuthData has length divisible by 16.

AddAuthData = 00 1D 2B DC 84 21 43 02 00 00 00 00 48 DE AC FF FF
01 00 00 00 00 48 DE AC 06 05 00 00 00 01 00

- d) Form the padded message PlaintextData by right-concatenating the octet string m with the smallest non-negative number of all-zero octets so that the octet string PlaintextData has length divisible by 16:

PlaintextData = CE 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00

- e) Form the message AuthData consisting of the octet strings AddAuthData and PlaintextData:

AuthData = 00 1D 2B DC 84 21 43 02 00 00 00 00 48 DE AC FF FF 01 00 00 00 00 48 DE
AC 06 05 00 00 00 01 00 CE 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00

C.3.3.2.4 Authentication transformation

The data AuthData that was established in C.3.3.2.3 is tagged using the tagging transformation as follows:

- a) Form the 1-octet Flags field:

$$\text{Flags} = 59$$

- b) Form the 16-octet B_0 field:

$$B_0 = 59 \parallel AC\ DE\ 48\ 00\ 00\ 00\ 00\ 01\ 00\ 00\ 00\ 05\ 06 \parallel 00\ 01$$

- c) Parse the message AuthData as $B_1 \parallel B_2 \parallel B_3$, where each message block B_i is a 16-octet string.
- d) The CBC-MAC value X_4 is computed as shown in Table C.4.

Table C.4—Computation of CBC-MAC value

i	B_i	X_i
0	59 AC DE 48 00 00 00 00 01 00 00 00 00 05 06 00 01	00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
1	00 1D 2B DC 84 21 43 02 00 00 00 00 48 DE AC FF	1C E4 F7 E4 FC 48 74 6D 0C 22 20 5D E8 DB B9 B0
2	FF 01 00 00 00 00 48 DE AC 06 05 00 00 00 01 00	16 EC 61 6D 5A C1 1A A0 4B 30 89 09 5D D5 7F 89
3	CE 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00	49 C3 1D 64 A5 A0 12 58 5B 07 78 B8 CD FE CE A8
4	—	D6 06 7B B5 9B 57 03 9C 00 98 0A 5D B3 63 BB 80

- e) The authentication tag T is the result of omitting all but the leftmost $M = 8$ octets of the CBC-MAC value X_4 :

$$T = D6\ 06\ 7B\ B5\ 9B\ 57\ 03\ 9C$$

C.3.3.2.5 Encryption transformation

The data PlaintextData is encrypted using the encryption transformation as follows:

- a) Form the 1-octet Flags field:

$$\text{Flags} = 01$$

- b) Define the 16-octet A_i fields as shown in Table C.5.

Table C.5— A_i fields

i	A_i
0	01 AC DE 48 00 00 00 00 01 00 00 00 00 05 06 00 00
1	01 AC DE 48 00 00 00 00 01 00 00 00 00 05 06 00 01

- c) Parse the message PlaintextData as M_1 , where each message block M_i is a 16-octet string.

- d) The cipher text block C_1 is computed as shown in Table C.6.

Table C.6—Computation of cipher text

i	AES(Key, A _i)	$C_i = AES(Key, A_i) \oplus M_i$
1	16 A9 67 B4 0F F9 72 DE B1 CB 46 E7 09 FD EB FF	D8 A9 67 B4 0F F9 72 DE B1 CB 46 E7 09 FD EB FF

- e) The string Ciphertext is the result of omitting all but the leftmost $l(m) = 1$ octet of the string C_1 :

Ciphertext = D8

- f) Define the 16-octet encryption block S_0 :

$S_0 = E(Key, A_0) = 99\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00$

- g) The encrypted authentication tag U is the result of XORing the string consisting of the leftmost $M = 8$ octets of S_0 and the authentication tag T :

$U = 4F\ DE\ 52\ 90\ 61\ F9\ C6\ F1$

C.3.3.2.6 Output

The output is as follows:

$c = D8\ ||\ 4F\ DE\ 52\ 90\ 61\ F9\ C6\ F1$.

C.3.3.3 AEAD mode decryption and authentication checking transformation

C.3.3.3.1 Inputs

The inputs to the AEAD mode inverse transformation are as follows:

- a) The key Key of size keylen = 128 bits to be used:

Key = C0 C1 C2 C3 C4 C5 C6 C7 C8 C9 CA CB CC CD CE CF

- b) The nonce N of $15 - L = 13$ octets to be used:

Nonce = AC DE 48 00 00 00 00 01 || 00 00 00 05 || 06

- c) The octet string c of length $l(c) = 9$ octets to be used:

$c = D8\ 4F\ DE\ 52\ 90\ 61\ F9\ C6\ F1$

- d) The octet string a of length $l(a) = 29$ octets to be used:

$a = 2B\ DC\ 84\ 21\ 43\ 02\ 00\ 00\ 00\ 00\ 48\ DE\ AC\ FF\ FF\ ||\ 01\ 00\ 00\ 00\ 00\ 00\ 48\ DE\ AC\ ||\ 06\ ||\ 05\ 00\ 00\ 00\ ||\ 01$

C.3.3.3.2 Actions

The AEAD mode inverse transformation involves the execution, in order, of a decryption transformation, as defined in C.3.3.3.3 and an authentication checking transformation as defined in C.3.3.3.4.

C.3.3.3.3 Decryption transformation

The decryption transformation involves the following steps, in order:

- a) Parse the message c as $C \parallel U$, where the rightmost string U is an 8-octet string:

$$C = D8$$

$$U = 4F\ DE\ 52\ 90\ 61\ F9\ C6\ F1$$

- b) Form the padded message CiphertextData by right-concatenating the string C with the smallest non-negative number of all-zero octets so that the octet string CiphertextData has length divisible by 16:

$$\text{CiphertextData} = D8\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00$$

- c) Form the 1-octet Flags field:

$$\text{Flags} = 01$$

- d) Define the 16-octet A_i fields as shown in Table C.7.

Table C.7— A_i fields

i	A_i
0	01 AC DE 48 00 00 00 00 01 00 00 00 05 06 00 00
1	01 AC DE 48 00 00 00 00 01 00 00 00 00 05 06 00 01

- e) Parse the message CiphertextData as C_1 , where each message block C_i is a 16-octet string.
- f) The plaintext block P_1 is computed as shown in Table C.8.

Table C.8—Computation of plaintext

i	$\text{AES}(\text{Key}, A_i)$	$P_i = \text{AES}(\text{Key}, A_i) \oplus C_i$
1	16 A9 67 B4 0F F9 72 DE B1 CB 46 E7 09 FD EB FF	CE 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00

- g) The octet string m is the result of omitting all but the leftmost $l(m) = 1$ octet of the string P_1 :

$$m = CE$$

- h) Define the 16-octet encryption block S_0 :

$$S_0 = E(\text{Key}, A_0) = 99\ D8\ 29\ 25\ FA\ AE\ C5\ 6D\ 17\ 93\ 04\ 21\ 3B\ 88\ 69\ 35$$

- i) The purported authentication tag T is the result of XORing the string consisting of the leftmost $M = 8$ octets of S_0 and the octet string U :

$$T = D6\ 06\ 7B\ B5\ 9B\ 57\ 03\ 9C$$

C.3.3.3.4 Authentication checking transformation

The authentication checking transformation involves the following steps, in order:

- a) Form the message AuthData using the input transformation in C.3.3.2.3, with as inputs the string a and the octet string m that was established in C.3.3.3.3 [step g]:

$$\begin{aligned} \text{AuthData} = & 00\ 1D\ 2B\ DC\ 84\ 21\ 43\ 02\ 00\ 00\ 00\ 00\ 48\ DE\ AC\ FF\ FF\ 01\ 00\ 00\ 00\ 00\ 48\ DE \\ & AC\ 06\ 05\ 00\ 00\ 00\ 01\ 00\ CE\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00\ 00 \end{aligned}$$

- b) Use the authentication transformation in C.3.3.2.4 with as input the message AuthData to compute the authentication tag MACTag:

MACTag = D6 06 7B B5 9B 57 03 9C

- c) Compare the output tag MACTag resulting from this transformation with the tag T that was established in C.3.3.3.3 [step i]:

$T = D6\ 06\ 7B\ B5\ 9B\ 57\ 03\ 9C = \text{MACTag}$

C.3.3.3.5 Output

Because $\text{MACTag} = T$, output “valid”, accept the octet strings a and m , and accept one of the key sharing group member(s) as the source of a and m .

C.4 Security processing operation

C.4.1 Beacon frame

This is the same example as C.3.2, but intermediate steps are omitted.

MHR of the Beacon frame with Frame Version field of 0b01, and Security Enabled. Destination address is omitted. Source address is 0xACDE480000000001 with Pan ID of 0x4321.

Auxiliary Security Header using security level of Mic64, Key Id Mode 0 - Implicit, Frame Counter field of 0x00000005, using key of 0xC0C1C2C3C4C5C6C7C8C9CACBCCDCECF.

- Nonce: AC DE 48 00 00 00 00 01 00 00 00 05 02
- Beacon frame: 08 D0 84 21 43 01 00 00 00 00 48 DE AC || 02 05 00 00 00 || 55 CF 00 00 51 52 53 54
- Secured beacon frame: 08 D0 84 21 43 01 00 00 00 00 48 DE AC || 02 05 00 00 00 || 55 CF 00 00 51 52 53 54 || 22 3B C1 EC 84 1A B5 53

C.4.2 MAC Command frame

This is same example as C.3.3, but intermediate steps are omitted.

MHR of the MAC Command frame with Frame Version field of 0b01, Security Enabled, and Ack Requested. Destination address is 0xACDE480000000002 with Pan ID of 0x4321. Source address is 0xACDE480000000001 with Pan ID of 0xFFFF.

Auxiliary Security Header using security level of Encrypted Mic64, Key Id Mode 0 - Implicit, Frame Counter field of 0x00000005, using key of 0xC0C1C2C3C4C5C6C7C8C9CACBCCDCECF.

- Nonce: AC DE 48 00 00 00 00 01 00 00 00 05 06
- MAC Command frame: 2B DC 84 21 43 02 00 00 00 00 48 DE AC FF FF 01 00 00 00 00 48 DE AC || 06 05 00 00 00 || 01 CE
- Secured MAC Command frame: 2B DC 84 21 43 02 00 00 00 00 48 DE AC FF FF 01 00 00 00 00 48 DE AC || 06 05 00 00 00 || 01 D8 || 4F DE 52 90 61 F9 C6 F1

C.4.3 MAC Command frame

This is an example of Enhanced Beacon command using Enhanced Beacon Filter IE.

MHR of the MAC Command frame with Frame Version field of 0b10, Security Enabled, and IE Present. Destination address is 0xFFFF with Pan ID of 0x4321. Source address is 0xACDE480000000001 with Pan ID of 0x4321.

Auxiliary Security Header using security level of Encrypted Mic128, Key Id Mode 0 - Implicit, Frame Counter field of 0x00000006, using key of 0xC0C1C2C3C4C5C6C7C8C9CACBCCCDCECF.

- Nonce: AC DE 48 00 00 00 00 01 00 00 00 06 07
- MAC Command frame: 0B EA 85 21 43 FF FF 21 43 01 00 00 00 00 48 DE AC || 07 06 00 00 00 || 00 3F || 03 88 01 1E 01 00 F8 07
- Secured MAC Command frame: 0B EA 85 21 43 FF FF 21 43 01 00 00 00 00 48 DE AC || 07 06 00 00 00 || 00 3F || E7 42 CC 07 1A 38 94 0D || 34 74 60 6E 7F E3 A1 55 BF 10 79 54 B9 C3 CD 58

C.4.4 MAC Command frame

This is same example as last one, but this one is using Pan ID Compression and will omit the source PAN ID.

MHR of the MAC Command frame with Frame Version field of 0b10, Security Enabled, PAN ID Compression, and IE Present. Destination address is 0xFFFF with Pan ID of 0x4321. Source address is 0xACDE480000000001.

Auxiliary Security Header using security level of Encrypted Mic128, Key Id Mode 0 - Implicit, Frame Counter field of 0x00000007, using key of 0xC0C1C2C3C4C5C6C7C8C9CACBCCCDCECF.

- Nonce: AC DE 48 00 00 00 00 01 00 00 00 07 07
- MAC Command frame: 4B EA 86 21 43 FF FF 01 00 00 00 00 48 DE AC || 07 07 00 00 00 || 00 3F || 03 88 01 1E 01 00 F8 07
- Secured MAC Command frame: 4B EA 86 21 43 FF FF 01 00 00 00 00 48 DE AC || 07 07 00 00 00 || 00 3F || 3E D2 AD F2 5F 3A 12 2C || 81 4A DC 9A EB BE 26 38 41 B8 46 33 5F B0 76 18

C.4.5 Enhanced Beacon frame

This is example of Enhanced Beacon used in the TSCH. This is just authenticated not encrypted, because TSCH beacons cannot be encrypted because the data in them is needed for joining the network. The security processing is bit more difficult because the recipient needs to know the ASN before it can verify the MIC of the frame. Because this is TSCH Beacon, this will include TSCH Synchronization IE inside, which will tell the ASN. This frame is using ASN of 0x123456789A.

MHR of the Beacon frame with Frame Version field of 0b10, Security Enabled, PAN ID Compression, and IE Present. Destination address is 0xFFFF with Pan ID of 0x4321. Source address is 0xACDE480000000001.

Auxiliary Security Header using security level of Mic128, Key Id Mode 1 with key index of 1, ASN 0x123456789A In Nonce, using key of 0xC0C1C2C3C4C5C6C7C8C9CACBCCCDCECF.

- Nonce: AC DE 48 00 00 00 00 01 12 34 56 78 9A
- Beacon frame: 48 EA 87 21 43 FF FF 01 00 00 00 00 48 DE AC || 6B 01 || 00 3F || 1A 88 06 1A 9A 78 56 34 12 04 01 1C 01 0A 1B 01 01 64 00 01 00 00 00 00 0F 01 C8 00

- Secured Beacon frame: 48 EA 87 21 43 FF FF 01 00 00 00 00 48 DE AC || 6B 01 || 00 3F || 1A 88 06 1A 9A 78 56 34 12 04 01 1C 01 0A 1B 01 01 64 00 01 00 00 00 00 0F 01 C8 00 || F5 40 8E FD C4 AA C6 D1 1B 7E F7 82 9F AD F5 AC

C.4.6 Data frame

This is example of Data frame using both header (not encrypted) and payload IEs (encrypted). This also uses PAN ID Compression of extended addresses, meaning there is no PAN ID at all. The header IE is Global Time IE, and the Payload IE is the Mac Metrics IE telling the number of octets sent. The contents of the Data frame is string “This is data”.

MHR of the Data frame with Frame Version field of 0b10, Security Enabled, Ack Requested, PAN ID Compression, and IE Present. Destination address is 0xACDE480000000002. Source address is 0xACDE480000000001.

Auxiliary Security Header using security level of Encrypted Mic64, Key Id Mode 1 with key index of 1, Frame Counter field of 0x00000008, using key of 0xC0C1C2C3C4C5C6C7C8C9CACBCCCDCECF.

- Nonce: AC DE 48 00 00 00 00 01 00 00 00 08 06
- Data frame: 69 EE 85 02 00 00 00 00 48 DE AC 01 00 00 00 00 48 DE AC || 0E 08 00 00 00 01 || 84 14 34 FF 3F 5C 00 3F || 07 88 05 1F 01 E8 03 00 00 00 F8 54 68 69 73 20 69 73 20 64 61 74 61
- Secured Data frame: 69 EE 85 02 00 00 00 00 48 DE AC 01 00 00 00 00 48 DE AC || 0E 08 00 00 00 01 || 84 14 34 FF 3F 5C 00 3F || 9D 1E C5 A2 A0 52 3A BE 64 0A A4 DB 7C 47 79 31 15 56 B9 25 52 0B D1 || 58 A4 15 3B B3 1D C4 D3

C.4.7 Ack frame

This example of an Ack frame uses Header IEs and Data. The header IE used is the TSCH Time Correction IE, but this example does not use the ASN in Nonce feature, so it is not an exact TSCH ACK frame. The data in Ack simply says “ACK”.

MHR of the Ack frame with Frame Version field of 0b10, Security Enabled, PAN ID Compression, Sequence Number Suppression, and IE Present. Destination address is 0xACDE480000000002. Source address is 0xACDE480000000001.

Auxiliary Security Header using security level of Encrypted Mic32, Key Id Mode 1 with key index of 1, Frame Counter field of 0x00000009, using key of 0xC0C1C2C3C4C5C6C7C8C9CACBCCCDCECF.

- ACK Payload: 41 43 4B
- Nonce: AC DE 48 00 00 00 00 01 00 00 00 09 05
- Data frame: 4A EF 02 00 00 00 00 00 48 DE AC 01 00 00 00 00 48 DE AC || 0D 09 00 00 00 01 || 02 0F 01 00 80 3F || 41 43 4B
- Secured ACK frame: 4A EF 02 00 00 00 00 00 48 DE AC 01 00 00 00 00 48 DE AC || 0D 09 00 00 00 01 || 02 0F 01 00 80 3F || 0B C7 5A || FE 9F CF FB

Annex D

(informative)

AEAD algorithm support

For a complete description of security algorithm processing for AES-128-CCM, AES-256-CCM, and legacy AES-128-CCM* see Annex B. References for processing descriptions of additional security algorithms are found in IEEE 802.15.4 ANA database [B2] as they are added to the *secAeadAlgorithm* enumeration (see Table 9-9).

This amendment makes changes to expand support for additional security algorithms:

- a) Added *secAeadAlgorithm* to the *secKeyDescriptor* (see Table 9-11) that identifies the algorithm being used with values defined in Table 9-9.
- b) Modified *secKey* to allow variable length keys.
- c) Modified procedures for securing and unsecuring frames to use the *secAeadAlgorithm* in the *secKeyDescriptor*.

NOTE—It is out of scope of this standard as to how the *secAeadAlgorithm* is added, changed, or removed from an instance of the *secKeyDescriptor*.

The following limitations are defined for *secAeadAlgorithm*:

- The security algorithm defined by *secAeadAlgorithm* should be an AEAD algorithm (see IETF RFC 5116 [B16]).
- The specific AEAD algorithm described by *secAeadAlgorithm* is defined in IEEE 802.15.4 ANA database [B2] and those algorithms should be sourced from the list of AEAD algorithms defined by the Internet Assigned Numbers Authority.³⁴
- The procedure for inclusion of IANA-defined security algorithms into IEEE 802.15.4 ANA database [B2] is defined in the IEEE 802.15 Operations Manual [B11].
- The *secKey* length for *secAeadAlgorithm* is variable.
- The nonce should be 13 octets and defined as described in 9.3.2.

³⁴ Available at <https://www.iana.org/assignments/aead-parameters/aead-parameters.xhtml>.

Annex E

(informative)

Protocol implementation conformance statement (PICS) proforma³⁵

E.1 Introduction

E.1.1 General

To evaluate the conformance of a particular implementation, it is necessary to have a statement of which capabilities and options have been implemented for a given standard. Such a statement is called a protocol implementation conformance statement (PICS).

E.1.2 Scope

This annex provides the PICS proforma for this standard in compliance with the relevant requirements.

E.1.3 Purpose

The supplier of a protocol implementation claiming to conform to this standard may complete the following PICS proforma and accompany it with the information necessary to identify fully both the supplier and the implementation.

The PICS of a protocol implementation is a statement of which capabilities and options of the protocol have been implemented. The statement is in the form of answers to a set of questions in the PICS proforma. The questions in a proforma consist of a systematic list of protocol capabilities and options as well as their implementation requirements. The implementation requirement indicates whether implementation of a capability is mandatory, optional, or conditional depending on options selected. When a protocol implementor answers questions in a PICS proforma, the implementor indicates whether an item is implemented and provides explanations if an item is not implemented.

E.2 Abbreviations and special symbols

Notations for requirement status:

M	Mandatory
O	Optional
O.n	Optional, but support of at least one of the group of options labeled by the same numeral <n> is required
N/A	Not applicable
X	Prohibited
“item”: (item number item number)	Conditional, status dependent upon the support marked for the “item” Applies to all item numbers listed

³⁵ Copyright release for PICS proforms: Users of this standard may freely reproduce the PICS proforma in this annex so that it can be used for its intended purpose and may further publish the completed PICS.

For example, FD1: O.1 indicates that if FD1 is implemented, then least one of the features labeled with O.1 is required to be implemented.

An example of a conditional status applying to all the items is as follows:

(FD1 || FD2 || FD6): M

This is equivalent to the following conditions:

FD1: M
FD2: M
FD6: M

E.3 Instructions for completing the PICS proforma

If it is claimed to conform to this standard, the actual PICS proforma to be filled in by a supplier should be technically equivalent to the text of the PICS proforma in this annex and preserve the numbering, naming, and ordering of the PICS proforma.

A PICS that conforms to this annex should be a conforming PICS proforma completed in accordance with the instructions for completion given in this annex.

The main part of the PICS is a fixed-format questionnaire, divided into tables. Answers to the questionnaire are to be provided in the rightmost column, either by simply marking an answer to indicate a restricted choice (such as Yes or No) or by entering a value or a set or range of values.

E.4 Identification of the implementation

The Table E.1 is used to provide implementation information.

Table E.1—Implementation information

Implementation under test identification	
Implementation under test name:	
Implementation under test version:	
System under test identification	
System under test name:	
Hardware configuration:	
Operating system:	
Product supplier	
Name:	
Address:	

Table E.1—Implementation information (continued)

Implementation under test identification	
Telephone number:	
Email address:	
Additional information:	
Client	
Name:	
Address:	
Telephone number:	
Email address:	
Additional information:	
PICS contact person	
Name:	
Address:	
Telephone number:	
Email address:	
Additional information:	
PICS/System conformance statement	
Provide the relationship of the PICS with the system conformance statement for the system:	

E.5 Identification of the protocol

This PICS proforma applies to IEEE Std 802.15.4-2024.

E.6 Global statement of conformance

The implementation described in this PICS proforma meets all of the mandatory requirements of the referenced standard.

[] Yes

[] No

NOTE—Answering “No” indicates nonconformance to the specified protocol standard. Unsupported mandatory capabilities are to be identified in the following tables, with an explanation by the implementor explaining why the implementation is nonconforming.

The supplier will have fully complied with the requirements for a statement of conformance by completing the statement contained in this subclause. However, the supplier may find it helpful to continue to complete the detailed tabulations in the subclauses that follow.

E.7 PICS proforma tables

E.7.1 General

The following tables are composed of the detailed questions to be answered, which make up the PICS proforma.

E.7.2 Optional groups

The list of optional groupings are given in Table E.2.

Table E.2—List of optional groups

Group	Description
O.3	PHY
O.5	HRP UWB band
O.8	LE capabilities
O.9	LRP UWB mode
O.10	Channel number
O.11	LECIM PHY type
O.12	Modulation type
O.13	TRLE capabilities
O.14	Security algorithm

E.7.3 Functional device types

The requirements for the functional device types are described in Table E.3.

Table E.3—Functional device types

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
FD3	Support of extended address	7.1	M			
FD4	Assignment of short network address	10.21.2	O			
FD5	Support of short network address	7.2.2.9	O			
FD8	Enhanced frame support	7.2.2.10	O			

E.7.4 Major capabilities for the PHY

E.7.4.1 General

The requirements for the major PHY capabilities are given in this subclause.

E.7.4.2 PHY functions

The requirements for the PHY functions are described in Table E.4.

Table E.4—PHY functions

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
PLF1	Energy detection (ED)	11.2.6	O			
PLF2	Link quality indicator (LQI)	11.2.7	O			
PLF3	Clear channel assessment (CCA)	11.2.8	M			
PLF4	Ranging	10.29	O			
PLF4.1	Crystal characterization	10.29.1.6	PLF4: O			
PLF4.2	Dynamic preamble selection (DPS)	10.29.4	RF4: O			
PLF5	Default HRP UWB pulse shape	16.3	RF4: M			
PLF5.1	Chirp on UWB (CoU)	16.5.2	RF4: O			
PLF5.2	Continuous spectrum (CS)	16.5.3	RF4: O			

Table E.4—PHY functions (*continued*)

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
PLF5.3	Linear combination of pulses (LCP)	16.5.4	RF4: O			
PLF6	LRP UWB base mode	19.2.2	RF9: O.9			
PLF7	LRP UWB extended mode	19.2.3	RF9: O.9			
PLF8	LRP UWB long-range mode	19.2.4	RF9: O.9			

E.7.4.3 Radio frequency (RF)

The requirements for the PHY RF capabilities are described in Table E.5.

Table E.5—Radio frequency (RF)

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
RF1	BPSK PHY	Clause 14	O.3			
RF1.1	BPSK PHY in 868 MHz band	Table 11-1	RF1: M			
RF1.2	BPSK PHY in 915 MHz band	Table 11-1	RF1: M			
RF2	O-QPSK PHY	Clause 13	O.3			
RF2.1	O-QPSK PHY in 868 MHz or 915 MHz bands	Table 11-1	RF2: O			
RF2.2	O-QPSK PHY in 2450 MHz band	Table 11-1	RF2: O			
RF2.3	O-QPSK PHY in 2380 MHz band	Table 11-1	RF2: O			
RF2.4	O-QPSK PHY in 780 MHz band	Table 11-1	RF2: O			
RF3	CSS PHY	Clause 15	O.3			
RF3.1	CSS PHY 1 Mb/s	15.2.2	RF3: M			
RF3.2	CSS PHY 250 kb/s	15.2.2	RF3: O			
RF4	HRP UWB PHY	Clause 16	O.3			
RF4.1	HRP UWB PHY 250–750 MHz	Table 11-1, Table 11-9, 16.4	RF4: O.5			
RF4.2	HRP UWB PHY 3244–4742 MHz	Table 11-1, Table 11-9, 16.4	RF4: O.5			
RF4.3	HRP UWB PHY 5944–10 234 MHz	Table 11-1, Table 11-9, 16.4	RF4: O.5			
RF4.4	HRP UWB PHY 850 kb/s	16.2.4, 16.2.7	RF4: M			
RF4.5	HRP UWB PHY 110 kb/s rate	16.2.4, 16.2.7	O			

Table E.5—Radio frequency (RF) (continued)

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
RF4.6	HRP UWB PHY 6.8 Mb/s rate	16.2.4, 16.2.7	O			
RF4.7	HRP UWB PHY 27 Mb/s rate	16.2.4, 16.2.7	O			
RF6	GFSK PHY in 920 MHz band	Clause 17	O.3			
RF8	MSK PHY	Clause 18	O.3			
RF9	LRP UWB PHY in 6289.6–9185.6 band	Clause 19	O.3			
RF10	SUN PHY device	11.1	O.3			
RF10.1	SUN FSK	Clause 20	RF10: M			
RF10.2	SUN OFDM	Clause 21	RF10: O			
RF10.3	SUN O-QPSK	Clause 22	RF10: O			
RF10.4	SUN FSK Generic PHY	20.3	RF10.1: O			
RF10.5	Transmit and receive enhanced beacons using CSM	11.1.9	(FD8 RF10 MLF9.9): M			
RF10.6	At least one of the bands given in Table 11-1	11.1	RF10: M			
RF11	SUN PHY operating modes					
RF11.1	Operating mode #1 in one of the bands defined in Table 20-7 except 866 MHz band	20.3	RF10: M			
RF11.2	Operating mode #2 in bands defined in Table 20-7 except 866 MHz band	20.3	RF10: O			
RF11.3	Operating mode #3 in bands defined in Table 20-7	20.3	RF10: O			
RF11.4	Operating mode #1 and #2 when operated in one of the bands defined in Table 20-8	20.3	RF10: M			
RF11.5	Operating mode #3, #4, and #5 in one of the bands defined in Table 20-8	20.3	RF10: O			
RF11.6	Operating mode #1 and #2 in 866 MHz band as defined in Table 20-7	20.3	RF10: M			
RF11.7	Operating mode #5, #6, #7, #8, #9, #10, #11, and #12 in 920 MHz band as defined in Table 20-8 and Table 20-10	20.3	RF10: O			
RF12	SUN FSK options					
RF12.1	SUN FSK FEC	20.3.5	RF10.1: O RF10.4: O			

Table E.5—Radio frequency (RF) (continued)

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
RF12.2	SUN FSK interleaving	20.3.6	RF10.1: O RF10.4: O			
RF12.3	SUN FSK data whitening	20.4	RF10.1: O RF10.4: O			
RF12.4	SUN FSK mode switching	20.5	RF10.1: O RF10.4: O			
RF13	SUN OFDM operating modes					
RF13.1	Support for all BPSK and QPSK modes	21.3	RF10.2: M			
RF13.2	SUN OFDM frequency spreading	21.4.6	RF10.2: M			
RF14	SUN O-QPSK operating modes					
RF14.1	SpreadingMode DSSS	22.3.4	RF10.3: M			
RF14.2	RateMode zero	22.3.5	RF10.3: M			
RF15	LECIM PHY device	11.1	O.3			
RF15.1	LECIM DSSS	Clause 23	RF15: O.11			
RF15.2	LECIM FSK	Clause 24	RF15: O.11			
RF15.3	At least one of the bands given in Table 11-2 or Table 11-3	11.1	RF15: M			
RF16	LECIM DSSS options					
RF16.1	LECIM DSSS convolutional FEC	23.2.4	RF15.1: M			
RF16.2	LECIM DSSS interleaver	23.2.5	RF15.1: M			
RF16.3	LECIM DSSS differential encoding	23.2.6	RF15.1: M			
RF16.4	LECIM DSSS bit-to-symbol and symbol-to-chip encoding	23.2.7	RF15.1: M			
RF16.5	LECIM DSSS BPSK modulation	23.2.8.1	RF15.1: O.12			
RF16.6	LECIM DSSS O-QPSK modulation	23.2.8.2	RF15.1: O.12			
RF17	LECIM FSK options					
RF17.1	LECIM FSK FEC	24.4.5.2	RF15.2: O			
RF17.2	LECIM FSK interleaving	24.4.6	RF15.2: O			
RF17.3	LECIM FSK spreading	24.4.10	RF15.2: O			

Table E.5—Radio frequency (RF) (continued)

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
RF17.4	LECIM FSK data whitening	24.5	RF15.2: O			
RF17.5	LECIM FSK One of the valid operating modes	24.4	RF15.2: M			
RF17.6	LECIM FSK split mode	24.2	RF15.2: O			
RF17.7	LECIM FSK split mode FEC 1/2 CC	24.4.5.3.2	RF17.6: O			
RF17.8	LECIM FSK split mode FEC 1/3 CC	24.4.5.3.3	RF17.6: M			
RF17.9	LECIM FSK split mode FEC 1/4 LDPC	24.4.5.3.4	RF17.6: O			
RF17.10	LECIM FSK split mode interleaving	24.4.7	RF17.6: M			
RF17.11	LECIM FSK split mode fixed radio-burst distribution	24.4.7.2	RF17.6: O			
RF17.12	LECIM FSK precoding	24.4.9	RF17.6: M			
RF18	TVWS PHY device	11.1	O.3			
RF18.1	TVWS-FSK	Clause 25	RF18: O.12			
RF18.2	TVWS-OFDM	Clause 26	RF18: O.12			
RF18.3	TVWS-NB-OFDM	Clause 27	RF18: O.12			
RF18.4	Support at least one of the given bands	Table 10-47	RF18: M			
RF18.5	TVWS Ranging	10.29	RF18: O			
RF19	TVWS-FSK options					
RF19.1	Support for at least one of the modes	25.2, Table 25-3	RF18.1: M			
RF19.2	TVWS-FSK FEC and interleaving	25.2.3	RF18.1: O			
RF19.3	TVWS-FSK data whitening	25.2.4	RF18.1: O			
RF19.4	TVWS-FSK spreading	25.2.5	RF18.1: O			
RF20	TVWS-OFDM operating modes					
RF20.1	Support for MCS0, MCS1, and MCS2 modes	26.3, Table 26-3	RF18.2: M			
RF20.2	Support for MCS3, MCS4, and MCS5 modes	26.3, Table 26-3	RF18.2: O			
RF21	TVWS-NB-OFDM operating modes					
RF21.1	Support for at least one of the modes	27.3, Table 27-4	RF18.3: M			
RF22	RCC PHYs	Table 11-4	O.3			
RF22.1	RCC LMR GMSK	28.6.1	RF22: M			
RF22.2	RCC LMR 4-FSK	28.6.2	RF22: O			
RF22.3	RCC LMR QPSK	28.6.3	RF22: O			

Table E.5—Radio frequency (RF) (continued)

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
RF22.4	RCC LMR $\pi/4$ DQPSK	28.6.4	RF22: O			
RF22.5	RCC LMR DSSS DQPSK	28.6.5	RF22: O			
RF22.6	RCC LMR DSSS BPSK	Clause 29	RF22: O			
RF22.7	RCC LMR 9.6 kb/s	Table 11-4	RF22.1: M			
RF22.8	RCC LMR 19.2 kb/s	Table 11-4	RF22.1: O			
RF23	CMB PHY	Clause 30	O.3			
RF24	TASK PHY	Clause 31	O.3			
RF25	RS-GFSK PHY	Clause 32	O.3			

E.7.4.4 Channel capabilities for HRP UWB PHY

The HRP UWB channel requirements are described in Table E.6.

Table E.6—HRP UWB channels

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
PCH1	Channel number 0	Table 11-9	RF4.1: M			
PCH2	Channel number 1	Table 11-9	RF4.2: O			
PCH3	Channel number 2	Table 11-9	RF4.2: O			
PCH4	Channel number 3	Table 11-9	RF4.2: M			
PCH5	Channel number 4	Table 11-9	RF4.2: O			
PCH6	Channel number 5	Table 11-9	RF4.3: O			
PCH7	Channel number 6	Table 11-9	RF4.3: O			
PCH8	Channel number 7	Table 11-9	RF4.3: O			
PCH9	Channel number 8	Table 11-9	RF4.3: O			
PCH10	Channel number 9	Table 11-9	RF4.3: M			
PCH11	Channel number 10	Table 11-9	RF4.3: O			
PCH12	Channel number 11	Table 11-9	RF4.3: O			
PCH13	Channel number 12	Table 11-9	RF4.3: O			
PCH14	Channel number 13	Table 11-9	RF4.3: O			
PCH15	Channel number 14	Table 11-9	RF4.3: O			
PCH16	Channel number 15	Table 11-9	RF4.3: O			

E.7.4.5 Channel capabilities for LRP UWB PHY

The LRP UWB channel requirements are described in Table E.7.

Table E.7—LRP UWB channels

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
PCH17	Channel Number 0	Table 19-13	RF9: O.10			
PCH18	Channel Number 1	Table 19-13	RF9: O.10			
PCH19	Channel Number 2	Table 19-13	RF9: O.10			
PCH20	Channel Number 3	Table 19-14	RF9: O.10			
PCH21	Channel Number 4	Table 19-14	RF9: O.10			
PCH22	Channel Number 5	Table 19-14	RF9: O.10			
PCH23	Channel Number 6	Table 19-14	RF9: O.10			
PCH24	Channel Number 7	Table 19-14	RF9: O.10			
PCH25	Channel Number 8	Table 19-14	RF9: O.10			
PCH26	Channel Number 9	Table 19-14	RF9: O.10			

E.7.5 Major capabilities for the MAC sublayer

E.7.5.1 MAC sublayer functions

The MAC sublayer function requirements are described in Table E.8.

Table E.8—MAC sublayer functions

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
MLF1	Transmission of data	8.3.4, 8.3.5	M			
MLF1.1	Purge data	8.3.7, 8.3.8	O			
MLF2	Reception of data	8.3.6	M			
MLF2.1	Timestamp of incoming data	6.5.3, 8.3.6	O			
MLF3	Beacon management					
MLF3.1	Transmit beacons	10.2.4, 8.2.10	O			
MLF3.2	Receive beacons	Clause 6, 8.2.10	O			
MLF3.3	Beacon only period	10.2.2.4	RF18: O			
MLF4	Channel access mechanism	Clause 6, 6.3	M			

Table E.8—MAC sublayer functions (*continued*)

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
MLF5	Frame validation	8.3.6, 7.2.11, 6.6.2	M			
MLF6	Acknowledged frame delivery	Clause 6, 8.3.6, 6.6.3, 7.2.2.5,	M			
MLF7	Security					
MLF7.1	Unsecured mode	Clause 9	M			
MLF7.2	Secured mode	Clause 9	O			
MLF7.2.1	Data encryption	Clause 9	MLF7.2: O			
MLF7.2.2	Frame integrity	Clause 9	MLF7.2: M			
MLF7.3	AEAD algorithm agility	Clause 9	MLF7.2: O			
MLF7.3.1	AES-128-CCM*	Table 9-9	MLF7.3: O.14			
MLF7.3.2	AES-128-CCM	Table 9-9	MLF7.3: O.14			
MLF7.3.3	AES-256-CCM	Table 9-9	MLF7.3: O.14			
MLF8	Passive scanning	6.4.1.2	M			
MLF9	Optional features					
MLF9.2	Control, define, determine, and declare superframe structure	10.2	MLF9.11: O			
MLF9.2.1	Follow and use superframe structure	10.2	MLF9.11: O			
MLF9.3	TSCH capable	10.3	(MLF9.16 FD8): O			
MLF9.3.1	TSCH MAC management services	10.3.10	MLF9.3: M			
MLF9.3.2	TSCH channel access	10.3.2	MLF9.3: M			
MLF9.3.3	TSCH PAN formation	10.3.3	MLF9.3: M			
MLF9.3.4	Synchronization in TSCH PAN	10.3.5	MLF9.3: M			
MLF9.3.5	TSCH frame counter	9.4.3	MLF9.3: M			
MLF9.4	DSME capable	10.4	(MLF9.2 MLF9.11 MLF9.16 FD8): O			
MLF9.4.1	DSME MAC management service	10.4.13	MLF9.4: M			
MLF9.4.2	DSME multi- superframe structure	10.4.3	MLF9.4: M			
MLF9.4.3	Extended DSME	10.4.3	MLF9.4: O			
MLF9.5	LE capable	10.5	FD8: O			

Table E.8—MAC sublayer functions (*continued*)

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
MLF9.5.1	LE specific MAC sublayer service specification	10.5.7	MLF9.5: M			
MLF9.5.2	CSL capable	10.5	MLF9.5: O.8			
MLF9.5.3	LE superframe	10.5.2	MLF9.5: O.8			
MLF9.6	RIT capable	10.6	MLF9.5: O.8			
MLF9.6.1	Implicit RIT (I-RIT)	10.6.4	MLF9.6: O			
MLF9.7	TVWS	10.7	FD8: O			
MLF9.8	TMCTP	10.8	(MLF9.11 FD8): O			
MLF9.9	Multi-PHY management (MPM) for all coordinators when operating at more than 1% duty cycle	10.9	RF10: M			
MLF9.10	PCA	10.10	FD8: O			
MLF9.11	Slotted CSMA-CA	10.11	O			
MLF9.12	Suspendable CSMA-CA	10.12	O			
MLF9.13	RCCN superframe structure	10.13	(MLF9.11 FD8 RF22): O			
MLF9.14	SUN	10.14	(RF10 FD8): O			
MLF9.15	LECIM	10.15	(RF15 FD8): O			
MLF9.16	Channel hopping	10.16	O			
MLF9.17	PAN ID conflict resolution	10.17	O			
MLF9.18	ED scanning	10.18	O			
MLF9.19	Active scanning	10.19	O			
MLF9.20	Orphan scanning	10.20	O			
MLF9.21	Association and disassociation	10.21	O			
MLF9.21.1	Fast association	10.21.4	O			
MLF9.22	Indirect transfer	10.22	O			
MLF9.22.1	Store one transaction	10.22.2	O			
MLF9.23	Promiscuous mode	10.23	O			
MLF9.24	DA	10.24	FD8: O			
MLF9.25	Guaranteed timeslot (GTS) management	10.25	O			

Table E.8—MAC sublayer functions (*continued*)

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
MLF9.26	PHY parameter change notification	10.26	FD8: O			
MLF9.27	MAC metrics	10.27	O			
MLF9.27.1	MAC performance metrics PIB attributes	10.27.3	O			
MLF9.28	Spectrum resource measurement (SRM)	10.28	FD8: O			
MLF9.29	Ranging	10.29	O			
MLF9.29.1	DPS	10.29.4	RF4: O			
MLF9.30	Ranging in superframe structure	10.30	(MLF9.2 FD8): O			
MLF9.31	Secure transactions in ranging	10.31	IEEE Std 802.15.9: O			
MLF9.32	Multi-node ranging	10.32	FD8: O			
MLF9.33	Authenticated challenge-response ranging	10.33	O			
MLF9.34	Ranging message non-receipt exchange	10.34	FD8: O			
MLF9.35	Ranging ancillary information	10.35	FD8: O			
MLF9.36	Multiple message receipt confirmation in ranging	10.36	FD8: O			
MLF9.37	TRLE capability	10.37	O			
MLF9.37.1	Link extension for non-TRLE PAN	10.37.3	MLF9.37: O.13			
MLF9.37.2	Link extension for TRLE-enabled PAN	10.37.4	MLF9.37: O.13			
MLF9.37.3	TRLE MAC management service	10.37.5.3	MLF9.37: M			
MLF10	PSDU Fragmentation	23.3	RF15.1: M			

E.7.5.2 MAC frames

The MAC frame requirements are described in Table E.9.

Table E.9—MAC frames

Item number	Item description	Reference	Transmitter		Receiver	
			Status	Support N/A Yes No	Status	Support N/A Yes No
MF1	Beacon	7.3.1	O		O	
MF1.1	Enhanced Beacon	7.3.1	FD8: O		FD8: O	
MF2	Data	7.3.2	M		M	
MF3	Acknowledgment	7.3.3	M		M	
MF3.1	Enhanced Acknowledgment	7.3.3	FD8: M		FD8: M	
MF3.2	Multipurpose	7.3.5	FD8: O MLF9.5.2: M		FD8: O MLF9.5.2: M	
MF3.3	Extended	7.3.6	O		O	
MF4	Command format	7.3.4	M		M	
MF4.1	Association Request command	7.3.4, 10.21.5.1	MLF9.21: O		MLF9.21: O	
MF4.2	Association Response command	7.3.4, 10.21.5.2	MLF9.21: O		MLF9.21: O	
MF4.3	Disassociation Notification command	7.3.4, 10.21.5.3	MLF9.21: O		MLF9.21: O	
MF4.4	Data Request command	7.3.4, 10.22.4.1	MLF9.22: O		MLF9.22: O	
MF4.5	PAN ID Conflict Notification command	7.3.4, 10.17.4.1	MLF9.17: O		MLF9.17: O	
MF4.6	Orphan Notification command	7.3.4, 10.20.3.1	MLF9.20: O		MLF9.20: O	
MF4.7	Beacon Request command	7.3.4, 7.5.2	O		O	
MF4.8	Enhanced Beacon Request command	7.5.3	FD8: O		FD8: O	
MF4.9	Coordinator Realignment command	7.3.4, 7.5.4	O		O	
MF4.10	GTS request command	7.3.4, 10.25.9.1	MLF9.25: O		MLF9.25: O	
MF4.11	TRLE Management Request command	10.37.5.2.1	MLF9.37.2: M		MLF9.37.2: M	
MF4.12	TRLE Management Response command	10.37.5.2.2	MLF9.37.2: M		MLF9.37.2: M	
MF4.13	DSME Association Request command	10.4.12.1	MLF9.4: M		MLF9.4: M	
MF4.14	DSME Association Response command	10.4.12.2	MLF9.4: M		MLF9.4: M	

Table E.9—MAC frames (*continued*)

Item number	Item description	Reference	Transmitter		Receiver	
			Status	Support N/A Yes No	Status	Support N/A Yes No
MF4.15	DSME GTS Request command	10.4.12.3	MLF9.4: M		MLF9.4: M	
MF4.16	DSME GTS Response command	10.4.12.4	MLF9.4: M		MLF9.4: M	
MF4.17	DSME GTS Notify command	10.4.12.5	MLF9.4: M		MLF9.4: M	
MF4.18	DSME Information Request command	10.4.12.6	MLF9.4: M		MLF9.4: M	
MF4.19	DSME Information Response command	10.4.12.7	MLF9.4: M		MLF9.4: M	
MF4.20	DSME Beacon Allocation Notification command	10.4.12.8	MLF9.4: M		MLF9.4: M	
MF4.21	DSME Beacon Collision Notification command	10.4.12.9	MLF9.4: M		MLF9.4: M	
MF4.22	DSME Link Report command	10.4.12.10	MLF9.4: M		MLF9.4: M	
MF4.23	RIT Data Request command	10.6.6.1	MLF9.6: M		MLF9.6: M	
MF4.24	DBS Request command	10.8.5.1	(MLF9.8 RF18): M		(MLF9.8 RF18): M	
MF4.25	DBS Response command	10.8.5.2	(MLF9.8 RF18): M		(MLF9.8 RF18): M	
MF4.26	RIT Data Response command	10.6.6.2	MLF9.6: M		MLF9.6: M	
MF4.27	Vendor Specific command	7.5.5	O		O	
MF4.28	SRM Request command	10.28.7.1	MLF9.28: M		MLF9.28: M	
MF4.29	SRM Response command	10.28.7.2	MLF9.28: M		MLF9.28: M	
MF4.30	SRM Report command	10.28.7.3	MLF9.28: M		MLF9.28: M	
MF4.31	SRM Information command	10.28.7.4	MLF9.28: M		MLF9.28: M	
MF4.32	Ranging Verifier command	10.33.7.1	MLF9.33: M		MLF9.33: M	
MF4.33	Ranging Prover command	10.33.7.2	MLF9.33: M		MLF9.33: M	

Table E.9—MAC frames (*continued*)

Item number	Item description	Reference	Transmitter		Receiver	
			Status	Support N/A Yes No	Status	Support N/A Yes No
MF5	FCS					
MF5.1	2-octet FCS	7.2.11	NOT (RF10 RF18): M		NOT (RF10 RF18): M	
MF5.2	4-octet FCS	7.2.11	(RF10 RF15.2 RF18): M		(RF10 RF15.2 RF18): M	

E.7.5.3 MAC IEs

The MAC IE requirements are described in Table E.10.

Table E.10—MAC IEs

Item number	Item description	Reference	Transmitter		Receiver	
			Status	Support N/A Yes No	Status	Support N/A Yes No
MIE1	IEs	7.4	O, (MLF9.3 MLF9.4 MLF9.5.2 MLF9.6 MLF9.4.3 MLF9.9 MLF3.3 RF10 RF18 RF22): M		O, (MLF9.3 MLF9.4 MLF9.5.2 MLF9.6 MLF9.4.3 MLF9.9 MLF3.3 RF10 RF18 RF22): M	
MIE	Header IEs					
MIE2.1	Header IE format	7.4.2.1	MIE1: M		MIE1: M	
MIE2.2	Vendor Specific Header IE	7.4.2.2	O		O	
MIE2.3	CSL IE	10.5.5.1	MLF9.5.2: M		MLF9.5.2: M	
MIE2.4	RIT IE	10.6.5.1	MLF9.6:O		MLF9.6:O	
MIE2.5	DSME PAN Descriptor IE	10.4.11.1	MLF9.4: M		MLF9.4: M	
MIE2.6	Rendezvous Time IE	10.5.5.2	MLF9.5.2: M		MLF9.5.2: M	
MIE2.7	Time Correction IE	10.3.8.1	MLF9.4: M		MLF9.4: M	
MIE2.8	Extended DSME PAN Descriptor IE	10.4.11.2	MLF9.4: M		MLF9.4: M	

Table E.10—MAC IEs (*continued*)

Item number	Item description	Reference	Transmitter		Receiver	
			Status	Support N/A Yes No	Status	Support N/A Yes No
MIE2.9	Fragment Sequence Context Description (FSCD) IE	10.15.2.1	MLF10: M		MLF10: M	
MIE2.10	Simplified Superframe Specification IE	10.2.8.1	MLF9.4: M		MLF9.4: M	
MIE2.11	Simplified GTS Specification IE	10.25.8.1	MLF9.4: M		MLF9.4: M	
MIE2.12	LECIM Capabilities IE	10.15.2.2	RF15: M		RF15: M	
MIE2.13	TRLE Descriptor IE	10.37.5.1.1	MLF9.37: O		MLF9.37: O	
MIE2.14	RCC Capabilities IE	10.13.3.1	RF22: M		RF22: M	
MIE2.15	RCCN Descriptor IE	10.13.3.2	RF22: M		RF22: M	
MIE2.16	Global Time IE	7.4.2.3	MLF9.4: M		MLF9.4: M	
MIE2.17	DA IE	10.24.2.1	O		O	
MIE2.18	Ranging STS Seed and Data IE (RSSD IE)	10.29.7.1	MLF9.29: O		MLF9.29: O	
MIE2.19	Header Termination 1 IE	7.4.2.4	MIE1: M		MIE1: M	
MIE2.20	Header Termination 2 IE	7.4.2.5	MIE1: M		MIE1: M	
MIE3	Payload IEs					
MIE3.1	Payload IE format	7.4.3	MIE1: M		MIE1: M	
MIE3.2	Encapsulated Service Data Unit (ESDU) IE	7.4.3.2	MIE1: O		MIE1: O	
MIE3.3	MLME IE	7.4.3.3	MIE1: M		MIE1: M	
MIE3.4	Vendor Specific Nested IE	7.4.4.3	MIE1: O		MIE1: O	
MIE3.5	Payload Termination IE	7.4.3.4	MIE1: M		MIE1: M	
MIE4	Nested IEs					
MIE4.1	Format of Nested IE	7.4.4.1	MIE1: M		MIE1: M	

Table E.10—MAC IEs (continued)

Item number	Item description	Reference	Transmitter		Receiver	
			Status	Support N/A Yes No	Status	Support N/A Yes No
MIE4.2	TSCH Synchronization IE	10.3.9.1	MLF9.3: M		MLF9.3: M	
MIE4.3	TSCH Slotframe and Link IE	10.3.9.2	MLF9.3: M		MLF9.3: M	
MIE4.4	TSCH Timeslot IE	10.3.9.3	MLF9.3: M		MLF9.3: M	
MIE4.5	Hopping Timing IE	10.5.6.1	MLF9.5: M		MLF9.5: M	
MIE4.6	Enhanced Beacon Filter IE	7.4.4.2	FD8: O		FD8: O	
MIE4.7	MAC Metrics IE	10.27.2.1	MLF9.27: O		MLF9.27: O	
MIE4.8	All MAC Metrics IE	10.27.2.2	MLF9.27: O		MLF9.27: O	
MIE4.9	Coexistence Specification IE	10.9.4.1	MLF9.9: M		MLF9.9: M	
MIE4.10	SUN Device Capabilities IE	10.14.3.1	(MLF9.14 RF10): M		(MLF9.14 RF10): M	
MIE4.11	SUN FSK Generic PHY IE	10.14.3.2	(MLF9.14 RF10): O		(MLF9.14 RF10): O	
MIE4.12	Mode Switch Parameter IE	10.14.3.3	(MLF9.14 RF10): O		(MLF9.14 RF10): O	
MIE4.13	PHY Parameter Change IE	10.26.3.1	(MLF9.26 RF2.3): M		(MLF9.26 RF2.3): M	
MIE4.14	O-QPSK PHY Mode IE	10.26.3.2	(MLF9.26 RF2.3): M		(MLF9.26 RF2.3): M	
MIE4.15	PCA Allocation IE	10.10.3.1	MLF9.10: M		MLF9.10: M	
MIE4.16	LECIM DSSS Operating Mode IE	10.15.3.1	(MLF9.15 RF15.1): M		(MLF9.15 RF15.1): M	
MIE4.17	LECIM FSK Operating Mode IE	10.15.3.2	(MLF9.15 RF15.2): M		(MLF9.15 RF15.2): M	
MIE4.18	TVWS PHY Operating Mode Description IE	10.7.3.1	(MLF9.7 RF18): M		(MLF9.7 RF18): M	
MIE4.19	TVWS Device Capabilities IE	10.7.3.2	(MLF9.7 RF18): M		(MLF9.7 RF18): M	
MIE4.20	TVWS Device Category IE	10.7.3.3	(MLF9.7 RF18): M		(MLF9.7 RF18): M	
MIE4.21	TVWS Device Identification IE	10.7.3.4	(MLF9.7 RF18): M		(MLF9.7 RF18): M	

Table E.10—MAC IEs (continued)

Item number	Item description	Reference	Transmitter		Receiver	
			Status	Support N/A Yes No	Status	Support N/A Yes No
MIE4.22	TVWS Device Location IE	10.7.3.5	(MLF9.7 RF18): M		(MLF9.7 RF18): M	
MIE4.23	TVWS Channel Information Query IE	10.7.3.6	(MLF9.7 RF18): M		(MLF9.7 RF18): M	
MIE4.24	TVWS Channel Information Source IE	10.7.3.7	(MLF9.7 RF18): M		(MLF9.7 RF18): M	
MIE4.25	CTM IE	10.7.3.8	(MLF9.7 RF18): M		(MLF9.7 RF18): M	
MIE4.26	Timestamp IE	10.7.3.9	(MLF9.7 RF18): M		(MLF9.7 RF18): M	
MIE4.27	Timestamp Difference IE	10.7.3.10	(MLF9.7 RF18): M		(MLF9.7 RF18): M	
MIE4.28	TMCTP Specification IE	10.8.4.1	(MLF9.8 RF18): M		(MLF9.8 RF18): M	
MIE4.29	RCC PHY Operating Mode IE	10.13.4.1	(MLF9.13 RF22): M		(MLF9.13 RF22): M	
MIE4.30	Link Margin IE	10.28.6.1	MLF9.28: O		MLF9.28: O	
MIE4.31	RS-GFSK Device Capabilities IE	10.26.3.3	MLF9.26: O		MLF9.26: O	
MIE4.32	Multi-PHY IE	10.26.3.4	MLF9.26: O		MLF9.26: O	
MIE4.33	Vendor Specific Nested IE	7.4.4.3	O		O	
MIE4.34	SRM IE	10.28.5.1	MLF9.28: M		MLF9.28: M	
MIE4.35	LECIM FSK Split Operating Mode IE	10.15.3.3	(MLF9.15 RF17.6): M		(MLF9.15 RF17.6): M	
MIE4.36	Ranging Reply Time Instantaneous IE (RRTI IE)	10.29.8.1	MLF9.29: O		MLF9.29: O	
MIE4.37	Advanced Ranging Control IE (ARC IE)	10.32.9.1	MLF9.32: O		MLF9.32: O	
MIE4.38	Ranging Interval Update IE (RIU IE)	10.32.9.2	MLF9.32: O		MLF9.32: O	
MIE4.39	Ranging Round IE (RR IE)	10.32.9.3	MLF9.32: O		MLF9.32: O	

Table E.10—MAC IEs (*continued*)

Item number	Item description	Reference	Transmitter		Receiver	
			Status	Support N/A Yes No	Status	Support N/A Yes No
MIE4.40	Ranging Block Update IE (RBU IE)	10.32.9.4	MLF9.32: O		MLF9.32: O	
MIE4.41	Ranging Contention Phase Structure IE (RCPS IE)	10.32.9.5	MLF9.32: O		MLF9.32: O	
MIE4.42	Ranging Contention Maximum Attempts IE (RCMA IE)	10.32.9.6	MLF9.32: O		MLF9.32: O	
MIE4.43	Ranging STS Seed and Data IE (RSSD IE)	10.29.8.2	MLF9.29: O		MLF9.29: O	
MIE4.44	Ranging Change Request IE (RCR IE)	10.32.9.7	MLF9.32: O		MLF9.32: O	
MIE4.45	Ranging Device Management IE (RDM IE)	10.32.9.8	MLF9.32: O		MLF9.32: O	
MIE4.46	Ranging Request Measurement and Control IE (RRMC IE)	10.29.8.3	MLF9.29: O		MLF9.29: O	
MIE4.47	Ranging Measurement Information IE (RMI IE)	10.29.8.4	MLF9.29: O		MLF9.29: O	
MIE4.48	SP3 Ranging Request Reports IE (SRRR IE)	10.32.9.9	MLF9.32: O		MLF9.32: O	
MIE4.49	Ranging Channel and Preamble Code Selection IE (RCPCS IE)	10.29.8.5	MLF9.29: O		MLF9.29: O	
MIE4.50	Ranging Reply Time Negotiation IE (RRTN IE)	10.29.8.6	MLF9.29: O		MLF9.29: O	
MIE4.51	Ranging Message Non Receipt IE (RMNR IE)	10.34.2.1	MLF9.34: O		MLF9.34: O	
MIE4.52	Ranging Ancillary Information Message Counter and Type IE (RAICT IE)	10.35.2.1	MLF9.35: O		MLF9.35: O	

Table E.10—MAC IEs (*continued*)

Item number	Item description	Reference	Transmitter		Receiver	
			Status	Support N/A Yes No	Status	Support N/A Yes No
MIE4.53	Ranging Multiple Message Receipt Confirmation IE (RMMRC IE)	10.36.2.1	MLF9.36: O		MLF9.36: O	
MIE4.54	Authenticated Challenge-Response Ranging Control IE (ACRRC IE)	10.33.6.1	MLF9.33: O		MLF9.33: O	
MIE4.55	Ranging Descriptor IE (RD IE)	10.30.2.1	MLF9.30: O		MLF9.30: O	
MIE4.56	ChallengeRespons eTransfer IE	10.33.6.2	MLF9.33: O		MLF9.33: O	
MIE5	Long nested IEs					
MIE5.1	Long nested IE format	7.4.4.1	MIE1: M		MIE1: M	
MIE5.2	Vendor Specific Nested IE	7.4.4.3	MIE1: O		MIE1: O	
MIE5.3	Channel Hopping IE	10.16.2.1	MLF9.16: M		MLF9.16: M	

Annex F

(informative)

Geographic regional frequency band details

Geographic regions are listed in Table F.1 according to the frequency bands.

Table F.1—Frequency bands with geographic information

Band designation	Frequency band (MHz)	Country or region
470 MHz	470–510	China
863 MHz	863–870	Europe
866 MHz	865–868	India
867 MHz	866–869	Singapore
870 MHz	870–876	Europe
915 MHz	902–928	North America
915 MHz-a	902–928 (alternate)	North America and Mexico
915 MHz-b	902–907.5 & 915–928	Brazil
915 MHz-c	915–928	Australia and New Zealand
915 MHz-d	915–921	Europe
915 MHz-e	915–918	Philippines
919 MHz	919–923	Malaysia
920 MHz	920–928	Japan
920 MHz-a	920.5–924.5	China
920 MHz-b	920–925	Hong Kong, Singapore, Thailand, and Vietnam

NOTE—The PHY parameters as defined for the 902–928 (alternate) MHz band can be used in addition to the existing 902–928 MHz band.

Annex G

(informative)

STS generation

G.1 Introduction

This annex provides test vectors for use in ensuring that an HRP-ERDEV implementation is producing the correct STS. This is achieved by specifying, for an example seed (i.e., specific STS seed and data values), the resultant first two blocks of bits that are produced by the DRBG, and the BPSK modulation polarities that are subsequently applied to the associated first 256 transmitted pulses of the STS.

G.2 Test vectors for STS generation

This example specifies the first two blocks generated by the DRBG described in 16.2.9 using the following initialization:

STS seed = 14 14 86 74 D1 D3 36 AA F8 60 50 A8 14 EB 22 0F

data = 36 2E EB 34 C4 4F A8 FB D3 7E C3 CA 1F 9A 3D E4

Here, STS seed = *phyHrpUwbStsSeed*, and data = *phyHrpUwbStsVUpper96* || *phyHrpUwbStsVCounter*.

The associated value of the RSSD IE (as defined in 10.29.8.2) in its over-the-air octet transmission order is:

F9 36 2E EB 34 C4 4F A8 FB D3 7E C3 CA 1F 9A 3D E4 14 14 86 74 D1 D3 36 AA F8 60 50 A8 14 EB 22 0F

Where there is no Application Code field, so the V3P field is 1, the V2P field is 1, the V1P field is 1, the VCP field is 1, the SKP field is 1, the ACP field is 0, the CP field is 1, and the associated *phyHrpUwbStsVCounter* value is 1F 9A 3D E4.

DRBG Blocks:

B(0) = 0x7AA6F63EF917AE47115EB6FE3B5A5791

B(1) = 0x41DA0C7503566357EBF38B2C12BB3E92

C(0:255) = 011110101010011011110110001111011111001000101111010111001000111
00010001010111101011011011111100011101101011010010101110010001
0100000111011010000011000111010100000011010101100110001101010111
111010111110011100010110010110000100101011011001111010010010

After the transmission of 4096 STS pulses, (a ~64 µs long BPRF mode STS or a ~32 µs long HPRF mode STS), the counter will have updated 32 times resulting in a *phyHrpUwbStsVCounter* value of 1F 9A 3E 04, and the associated value of data = *phyHrpUwbStsVUpper96* || *phyHrpUwbStsVCounter* is then 36 2E EB 34 C4 4F A8 FB D3 7E C3 CA 1F 9A 3E 04.

G.3 Resulting STS modulation

Bits C(0:255) from G.2 are mapped to BPSK modulation polarities of the first 256 pulses of the STS, as described in 16.2.9.3. Symbols A(i) are then spread by $\delta_L = 8$ chips in BPRF mode, or $\delta_L = 4$ chips in HPRF mode. The resulting symbols A(i) for the example data are:

Annex H

(informative)

Channel assignment for SUN FSK operating mode #9, #10, #11, and #12 in 920 MHz band

H.1 Channel assignments

The channel assignments for these operating modes are shown in Figure H.1.

The 920 MHz band has three band edges because this band is divided into two sub-bands, 920.5 MHz to 922.3 MHz and 922.3 MHz to 928.1 MHz. Some channels are not used as shown in Figure H.1 because the channels across these band edges are prohibited to be used by ARIB STD-T108 [B5].

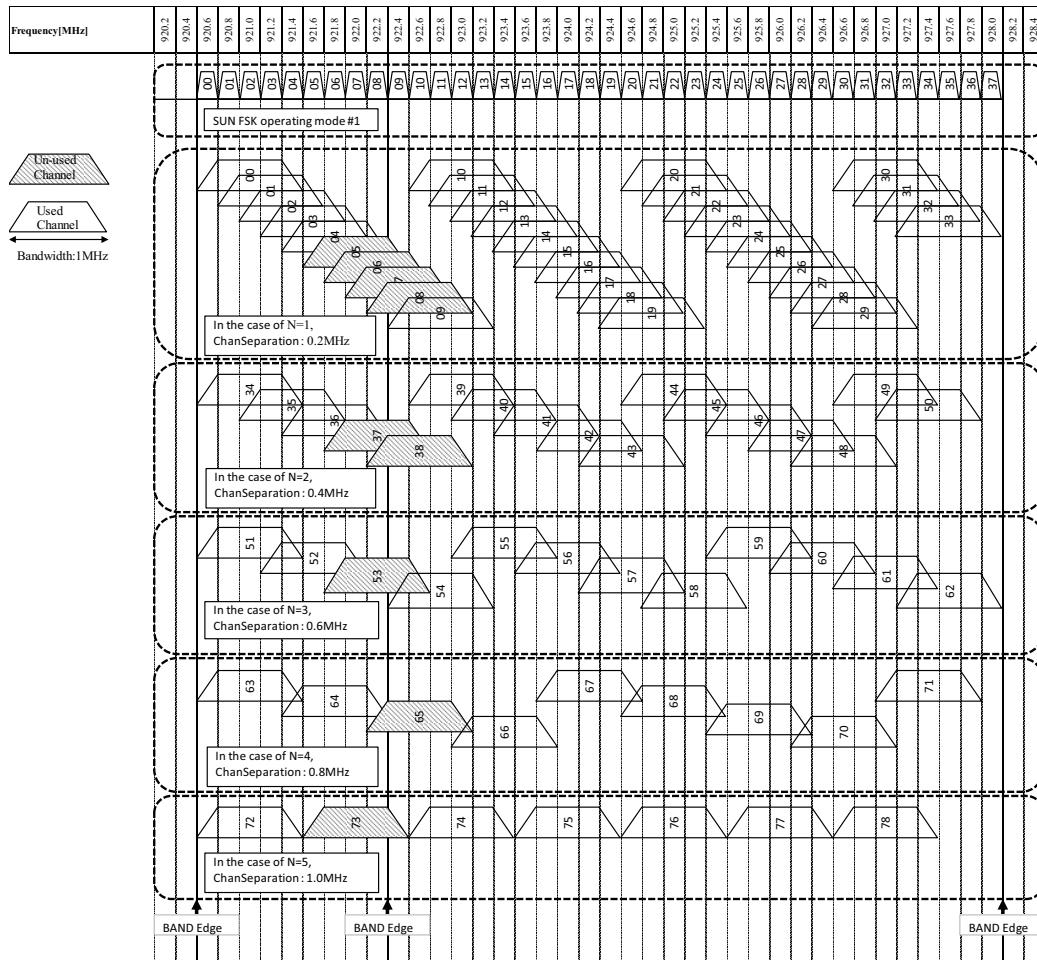


Figure H.1—Channel assignments for operating mode #9, #10, #11 and #12 in 920 MHz

RAISING THE WORLD'S STANDARDS

Connect with us on:

-  **Facebook:** facebook.com/ieeesa
-  **LinkedIn:** linkedin.com/groups/1791118
-  **Beyond Standards blog:** beyondstandards.ieee.org
-  **YouTube:** youtube.com/ieeesa

standards.ieee.org
Phone: +1 732 981 0060

