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IEEE Standard for Low-Rate Wireless Networks

Amendment 1: Enhanced Ultra Wideband (UWB) Physical Layers (PHYs) and Associated Ranging Techniques

IEEE Computer Society

Developed by the
LAN/MAN Standards Committee

IEEE Std 802.15.4z™-2020
(Amendment to IEEE Std 802.15.4™-2020)

IEEE

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Approved 4 June 2020

IEEE SA Standards Board

Abstract: This amendment enhances the UWB PHYs with additional coding options and improvements to increase the integrity and accuracy of ranging measurements. It also enhances the MAC to support control of time-of-flight ranging procedures and exchange ranging related information between the participating ranging devices.

Keywords: amendment, double-sided two-way ranging, DS-TWR, enhanced ranging device, ERDEV, HRP UWB PHY, HRP-ERDEV, IEEE 802.15.4™, IEEE 802.15.4z™, low power, low-rate wireless networks, LRP UWB PHY, LRP-ERDEV, multi-node ranging, precision ranging, ranging device, RDEV, RF, RFID, real time location systems, RTLS, single-sided two-way ranging, SS-TWR, time of flight, TOF, TOF integrity, two-way ranging, TWR, ultra wideband, UWB, wireless specialty networks, WSN

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Introduction

This introduction is not part of IEEE Std 802.15.4z-2020, IEEE Standard for Low-Rate Wireless Networks—Amendment 1: Enhanced Ultra Wideband (UWB) Physical Layers (PHYs) and Associated Ranging Techniques.

This amendment of IEEE Std 802.15.4-2020 specifies enhancements and enhanced modes of operation for the HRP UWB PHY and the LRP UWB PHY and associated ranging techniques in the MAC. The PHY enhancements include facilities to improve the integrity and accuracy of the ranging measurements. The MAC enhancements include specification of information element definitions to facilitate ranging information exchange, and changes to support the PHY enhancements.

These enhancements meet the needs of a wider set of applications where the integrity and accuracy of distance measurement is important.

The standard is widely used in a variety of applications that employ the ranging capabilities enabled by the UWB PHYs specified by IEEE Std 802.15.4-2020. Current users and product manufacturers have identified the need for improved efficiency, integrity, and accuracy of the existing ranging measurement methods in order to expand the usefulness of the standard for applications such as RFID and automotive, in particular, automotive remote control, and similar personal devices. These enhancements are also expected to open up new areas of application.

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Amendment 1: Enhanced Ultra Wideband (UWB) Physical Layers (PHYs) and Associated Ranging Techniques

(This amendment is based on IEEE Std 802.15.4™-2020.)

NOTE—The editing instructions contained in this amendment define how to merge the material contained therein into the existing base standard and its amendments to form the comprehensive standard.

The editing instructions are shown in ***bold italic***. Four editing instructions are used: change, delete, insert, and replace. ***Change*** is used to make corrections in existing text or tables. The editing instruction specifies the location of the change and describes what is being changed by using ~~strikethrough~~ (to remove old material) and underscore (to add new material). ***Delete*** removes existing material. ***Insert*** adds new material without disturbing the existing material. Deletions and insertions may require renumbering. If so, renumbering instructions are given in the editing instruction. ***Replace*** is used to make changes in figures or equations by removing the existing figure or equation and replacing it with a new one. Editing instructions, change markings, and this NOTE will not be carried over into future editions because the changes will be incorporated into the base standard.[1]

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

2. Normative references

Insert the following new normative references in alphabetical order:

IEEE Std 802.15.9™-2016, IEEE Recommended Practice for Transport of Key Management Protocol (KMP) Datagrams.[2]

ISO/IEC 7816-4:2013, Identification cards—Integrated circuit cards—Part 4: Organization, security and commands for interchange.[3]

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.[4]

[2]IEEE publications are available from The Institute of Electrical and Electronics Engineers (https://standards.ieee.org/).
[3]ISO publications are available from the International Organization for Standardization (https://www.iso.org/) and the American National Standards Institute (https://www.ansi.org/).
[4]JIS standards are available from The Japanese Standards Association, (https://www.jsa.or.jp/).

3. Definitions, acronyms, and abbreviations

3.1 Definitions

Insert the following new definitions in alphabetical order:

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

STS key: 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.

3.2 Acronyms and abbreviations

Insert the following new acronyms/abbreviations in alphabetical order:

AOA	angle of arrival
BPRF	base pulse repetition frequency
DCS	dynamic channel selection
DRBG	deterministic random bit generator
DS-TWR	double-sided two-way ranging
EPC	enhanced payload capacity
ERDEV	enhanced ranging capable device
HPRF	higher pulse repetition frequency
HRP-ERDEV	high rate pulse repetition frequency UWB PHY based enhanced ranging capable device
LRP-ERDEV	low rate pulse repetition frequency UWB PHY based enhanced ranging capable device
OWR	one-way ranging
PBFSK	pulsed binary frequency shift keying
PRP	pulse repetition period
PSR	preamble symbol repetitions
RBS	ranging beacon slot
RCM	ranging control message
RSTU	ranging scheduling time unit
SP3	scrambled timestamp sequence packet configuration option three
SS-TWR	single-sided two-way ranging
STS	scrambled timestamp sequence
TDOA	time difference of arrival
TOF	time of flight
TWR	two-way ranging

5. General description

5.7 Functional overview

5.7.3 Frame structure

Change paragraphs two and three of 5.7.3 as follows:

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 5-7.

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

6. MAC functional description

6.2 Channel access

Insert new subclause 6.2.11 after 6.2.10 as follows:

6.2.11 Beacon-enabled ranging with ERDEV

Support of beacon-enabled ranging for an enhanced ranging capable device (ERDEV) is optional. The ranging time structure for beacon-enabled ERDEV is shown in Figure 6-13a. 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 7.4.4.54.

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 comprised of ranging beacon slots (RBS). Each RBS has a duration specified in the ranging beacon (in multiples of the ranging scheduling time units (RSTU) defined in 6.9.1.5). 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 6.9.7). 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 6.9.7.2 and 6.9.7.3. 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.

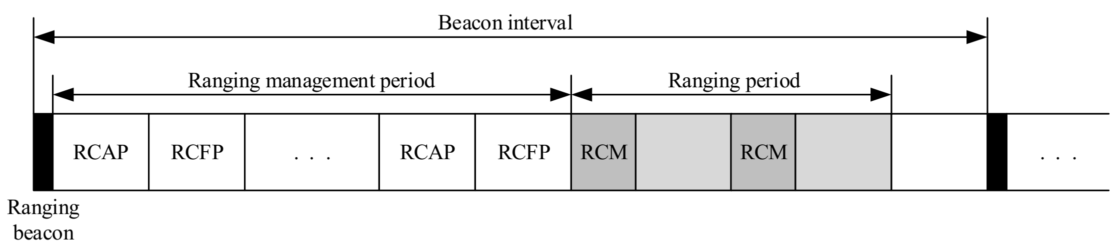

Figure 6-13a—Ranging time structure for beacon-enabled ranging with ERDEV

6.7 Transmission, reception, and acknowledgment

6.7.2 Reception and rejection

Insert the following paragraph at the start of 6.7.2:

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.

Insert the following paragraph at the end of 6.7.2:

In the case of an HRP-ERDEV configured to use SP3 format packets (where the packet does not include a 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 STS sequence in the received frame matches the expected STS sequence, 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.

6.7.4 Use of acknowledgments and retransmissions

6.7.4.3 Acknowledgment

Insert the following paragraph at the end of 6.7.4.3:

The acknowledgment transmission in response to an RFRAME shall be contained in an RFRAME.

Change the titles of 6.9 and 6.9.1, make the text of 6.9.1 into a new subclause 6.9.1.1, and change it as follows:

6.9 Ranging, relative positioning, and localization

6.9.1 Ranging ~~requirements~~ measurements

6.9.1.1 Overview

Support for ranging is optional. A device that supports ranging is called a ranging-capable device (RDEV). An RDEV shall support the ranging counter described in 6.9.1.3 and the figure of merit (FoM) described in 6.9.1.7. An RDEV may support optional crystal characterization described in 6.9.1.6 and the optional dynamic preamble code and channel selection (DPS) described in "Applications of IEEE Std 802.15.4" [B3]. 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.

~~Ranging is an optional feature.~~ This standard includes optional features to support relative positioning and localization. Accurate location may be achieved by a ranging-capable device (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 15 and Clause 18 optionally include facilities to enhance ranging, and these ERDEVs are referred to as the high rate pulse repetition frequency UWB PHY based enhanced ranging capable device (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 15.2.9, 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 6.9.8.

The fundamental measurements for ranging are achieved using a ~~Data frame Ack frame sequence~~ 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 ~~The Data frame has the Ranging field set to indicate ranging and~~ is referred to as a ranging frame (RFRAME). Generally, an RFRAME is indicated by the Ranging field being set in the PHR, however as described in 15.2, 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 STS packet configuration three (SP3). SP3 packets are treated as RFRAMEs.

Ranging capabilities are enabled in an RDEV ~~a ranging-capable device (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 ~~timestamp~~ reports to the next higher layer as a result of events at the device antenna. The times that are reported are ~~timestamp that is reported is~~ measured relative to the ranging marker (RMARKER). For all PHYs the RMARKER is defined to be the time when the beginning of the first symbol following the SFD ~~of the PHR~~ 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 8-90a) 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 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:

$$\frac{f_{\text{ref.remote}}}{f_{\text{ref.local}}} = \frac{L_{\text{segment.ideal}}}{\text{RxS1RangingCounter} - \text{RxS0RangingCounter}}$$

Insert new subclauses 6.9.1.2 through 6.9.1.7 before 6.9.2 as follows:

6.9.1.2 Ranging and localization methods

6.9.1.2.1 Preface

The ranging and localization methods supported by RDEVs and ERDEVs are based on the time-stamping capability. The three main time-based techniques for performing ranging and localization are as follows:

— SS-TWR, described in 6.9.1.2.2.
— DS-TWR, described in 6.9.1.2.3.
— OWR/TDOA, described in 6.9.1.2.5.

The following nomenclature is used:

— Initiator: the RDEV that starts ranging exchange by sending the first RFRAME in the exchange.
— Responder: the RDEV that responds to the ranging initiation RFRAME.

6.9.1.2.2 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 6-47a, 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.

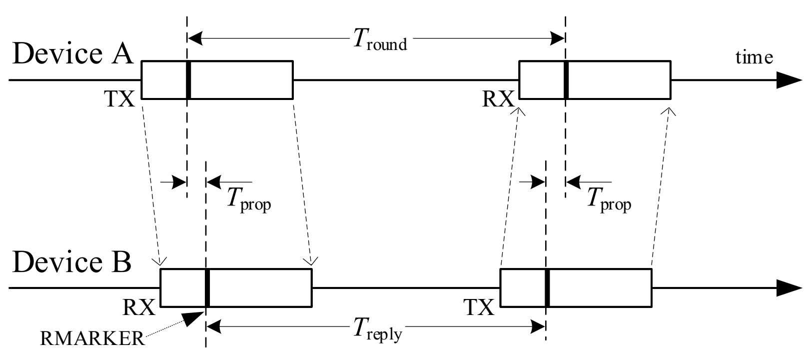

Figure 6-47a—SS-TWR

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 $\hat{T}_{\text{prop}}$ by the equation:

$$\hat{T}_{\text{prop}} = \frac{1}{2}(T_{\text{round}} - T_{\text{reply}})$$

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 "Applications of IEEE Std 802.15.4" [B3]. 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:

$$\hat{T}_{\text{prop}} = \frac{1}{2}(T_{\text{round}} - T_{\text{reply}} - (1 - C_{\text{offs}}))$$

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 6-48a and described in 6.9.6.3. 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 6-48b and described in 6.9.6.4. 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 6.9.6.5.

6.9.1.2.3 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 6-47b, 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.

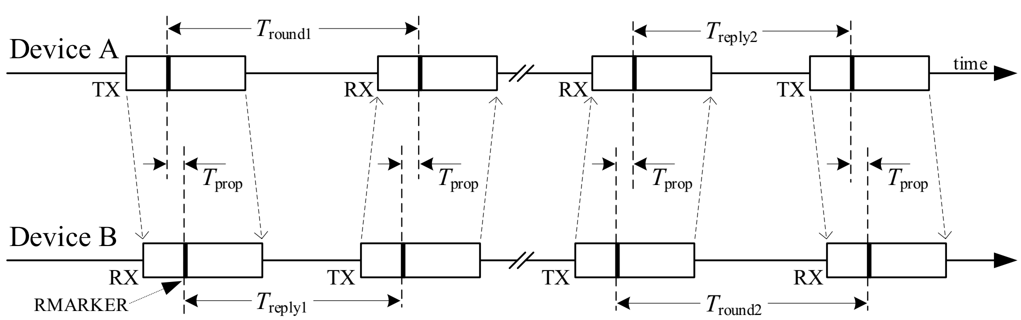

Figure 6-47b—DS-TWR

Each device precisely measures the transmission and reception times of the messages, and the resultant TOF may be estimated as $\hat{T}_{\text{prop}}$ 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 [B7a].

6.9.1.2.4 DS-TWR with three messages

The four messages of DS-TWR, shown in Figure 6-47b, 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 6-47c.

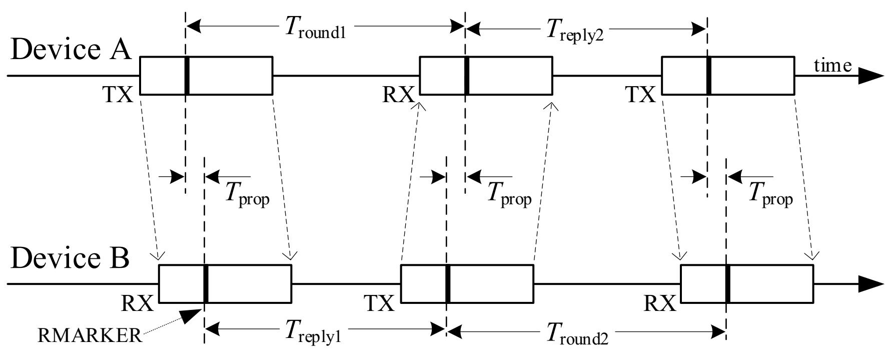

Figure 6-47c—DS-TWR with three messages

6.9.1.2.5 Time difference of arrival (TDOA)

TDOA is a technique to locate a mobile device, (e.g., a radio frequency identification (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.

6.9.1.3 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 6.9.1.4.

6.9.1.4 Ranging counter time unit

The time unit of the ranging counter as used in MCPS-DATA primitives and ranging time related IE 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.

6.9.1.5 Ranging scheduling time unit

The ranging scheduling time unit (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 6-4a.

Table 6-4a—PHY dependent RSTU values

PHY	RSTU
HRP UWB PHY	416 chips = $416 \div (499.2 \times 10^6) \approx 833.33$ ns
LRP UWB PHY	1 µs = 1 chip at 1 MHz basic chipping rate

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.

6.9.1.6 Crystal characterization

6.9.1.6.1 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 that crystal characterization is relevant only if it is characterizing the crystal that affects the ranging counter.

6.9.1.6.2 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 6.9.1.6.3. The precision shall be at least 19 bits.

6.9.1.6.3 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 6.9.1.6.2) of crystal offset values down to 100 parts per billion, or better. Greater precision is encouraged, as described in "Applications of IEEE Std 802.15.4" [B3].

6.9.1.7 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 6-47d.

Bits: 0–2	3–4	5–6	7
Confidence Level	Confidence Interval	Confidence Interval Scaling Factor	Extension

Figure 6-47d—Ranging FoM

The Confidence Level field conveys the probability that the RMARKER arrived during the Confidence Interval, as specified in Table 6-4b.

The Confidence Interval field specifies the confidence interval as defined in Table 6-4c. The duration of the Confidence Interval in Table 6-4c is the duration of the entire interval, not a plus or minus number.

The Confidence Interval Scaling Factor field is defined in Table 6-4d.

The overall confidence interval is obtained according to the formula:

Overall confidence interval = Confidence Interval × Confidence Interval Scaling Factor.

When the Extension field is zero, the fields have the meanings given in Table 6-4b, Table 6-4c, and Table 6-4d.

Table 6-4b—Confidence Level field

Confidence Level field value	Confidence level
0	No FoM
1	20%
2	55%
3	75%
4	85%

Table 6-4b—Confidence Level field *(continued)*

Confidence Level field value	Confidence level
5	92%
6	97%
7	99%

Table 6-4c—Confidence Interval field

Confidence Interval field value	Confidence interval
0	100 ps
1	300 ps
2	1 ns
3	3 ns

Table 6-4d—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 6-47e.

Bits: 0–6	7
Extension Value	Extension = 1

Figure 6-47e—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 8.2.16, 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.

6.9.2 Set-up activities before a ranging exchange

Change 6.9.2 as follows:

The mandatory part of ranging is limited to the generation of transmit and receive ranging counter time ~~timestamp~~ 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. ~~Prior to a two-way ranging exchange, both RDEVs involved in the exchange shall already have ranging enabled.~~ Furthermore, if the optional ~~dynamic preamble selection (~~DPS~~)~~ capability is to be used, it is assumed there has ~~there shall have~~ been some sort of coordination of the preamble and channel selection ~~preambles~~ prior to the TWR ~~two-way ranging~~ exchange. How this coordination ~~and enabling actually~~ is accomplished is up to the implementer. ~~beyond the scope of this standard. It may be perfectly acceptable to accomplish the coordination and enabling with a clock and a look-up table that says what a device should do at a particular time. Because coordination generally involves communication and because the PHYs are designed to achieve communication, it is natural to suggest that the PHY be used for coordination.~~ The Ranging Channel and Preamble Code Selection IE (RCPCS IE), as specified in 7.4.4.48, 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.

6.9.3 Finish-up activities after a ranging exchange

Change 6.9.3 as follows:

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 ~~a timestamp report~~. To compute the TOF ~~accomplish anything useful~~, both of these values are needed ~~those timestamp reports shall eventually come to be~~ at the ~~same~~ node where the computations are performed. How this movement of these values ~~timestamp reports~~ is accomplished is ~~beyond the scope of this standard~~ up to the implementer. ~~Timestamp reports are just data. Because movement of data involves communication and because the PHYs are designed to achieve communication, it is natural to suggest that the PHY be used for the final consolidation of timestamp reports.~~ Out-of-band signaling as well as custom messages or the Ranging Measurement Information IE (RMI IE), as specified in 7.4.4.46, can be used for this purpose as described in 6.9.6.3.

~~The application is responsible for enabling the ranging mode in the RDEV before a ranging exchange. After a ranging exchange, the application is again responsible for disabling the ranging mode in the RDEV. If the application fails to disable the ranging mode in the RDEV, there will be no algorithmic harm. Ranging mode is fully compatible with other uses of the RDEV, and the only result of leaving ranging enabled when it is not really being used is that the RDEV will generate useless timestamp reports while potentially consuming more power.#~~

Change the title of 6.9.4 as follows:

6.9.4 Managing DPS and DCS

Insert a new subclause heading 6.9.4.1 to contain the existing text and figure from 6.9.4 as follows:

6.9.4.1 Managing DPS

Change the first paragraph of 6.9.4 (now 6.9.4.1) as follows:

Figure 6-48 shows a suggested message sequence for TWR ~~two-way ranging~~. 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.

Replace Figure 6-48 with a new figure as follows:

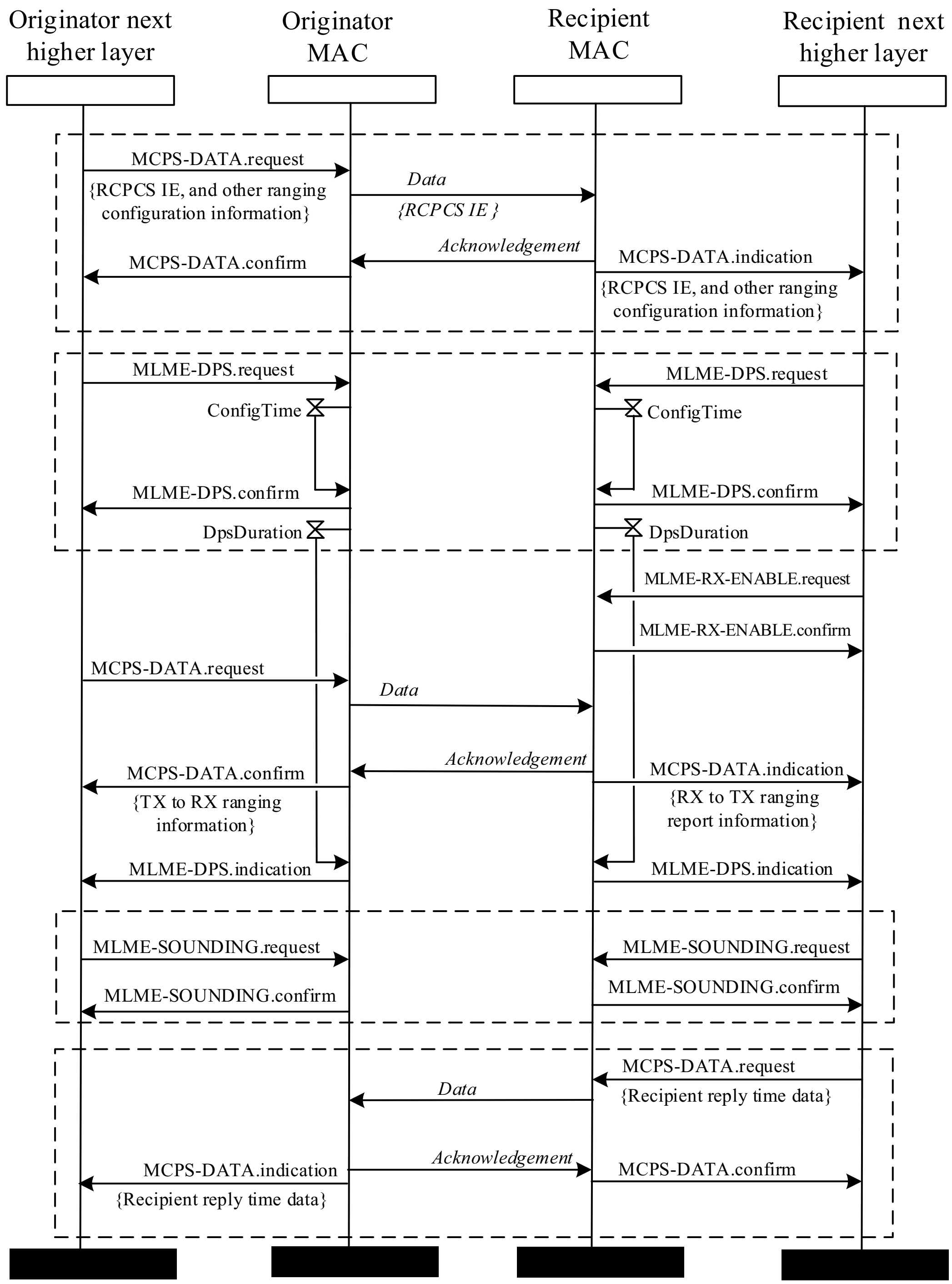

Figure 6-48—A message sequence for ranging

Change paragraphs two and three of 6.9.4 (now 6.9.4.1) as follows:

The top dotted box in Figure 6-48 illustrates the use of a data exchange to effect the coordination of the preamble codes and channel ~~preambles~~ to be used for a TWR ~~two-way ranging~~ exchange. The coordination ~~of preambles~~ is needed only when using the optional DPS capability of the PHY. As illustrated in Figure 6-48, for the ERDEV, the choice of preamble code and channel number can be exchanged using the RCPCS IE (described in 7.4.4.48). 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 ranging procedures in 6.9.6 and 6.9.7 describe mechanisms provided by this standard through which this can be achieved. The second from the top dotted box in Figure 6-48 illustrates the use of the MLME-DPS.request, as described in 8.2.15.2, and the MLME-DPS.confirm, as described in 8.2.15.3. Use of these primitives is unique to the optional DPS mode of 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 RCPCS IE. It is the responsibility of the next higher layer to ensure that the channel selection 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 6-48, both of the devices ~~PHYs~~ have switched to use the alternative ~~from the normal length preamble symbols to long~~ preamble symbols and/or channel number as selected by the MLME-DPS.request. This is desirable behavior intended to help hide the ~~PHYs'~~ transmissions from other ~~malicious~~ nodes in the network and protect the devices ~~PHYs~~ from transmissions by other ~~malicious~~ nodes in the network. A side effect of this mode is that neither device ~~PHYs~~ can communicate with the rest of the network. To prevent the devices from losing connectivity ~~PHYs from becoming lost~~ as a result of this ~~optional~~ behavior, the MAC sublayers on both sides of the link shall initiate timers after issuing the MLME-DPS.confirm with Status of SUCCESS ~~sending the frame (for the originator) or receiving the frame (for the recipient)~~. If the timer duration is exceeded before the MAC sublayer issues ~~receives~~ the MCPS-DATA.confirm~~comfirm~~ (for the originator) or the MCPS-DATA.indication primitive (for the recipient), then the MAC sublayer shall initiate a MLME-DPS.indication to the next higher layer as described in 8.2.15.4. Not shown in Figure 6-48, 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~~. Most typically, this MLME-DPS.request primitive would be part of the finish-up activities and would have both TxDpsIndex and RxDpsIndex set to zero~~ to return the PHYs to using the *phyCurrentCode* and *phyCurrentChannel* from the PIB. ~~Also not shown in Figure 6-48, another responsibility of the application is to initiate a MLME-DPS.request primitive in response to an MLME-DPS.indication. Most typically, this MLME-DPS.request primitive would have both TxDpsIndex and RxDpsIndex set to zero and return the PHY to using *phyCurrentCode* from the PIB.~~

Change the title and text of 6.9.5 as follows:

6.9.5 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 6.9.6 and 6.9.7. 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 6-48 starting just after ~~below~~ the MLME-DPS exchange. The application is responsible for initiating the MLME-RX-ENABLE.request primitive, as described in 8.2.10.2, with RangingControl ~~RangingRxControl~~ equal to RANGING_ON. Once the RDEV has received the MLME-RX-ENABLE.request primitive with RangingControl ~~RangingRxControl~~ equal to RANGING_ON, all future RFRAMEs received by the RDEV shall generate TX and RX ranging counter ~~timestamp~~ reports until ranging is disabled.

At the initiator, the application is responsible for initiating a MCPS-DATA.request primitive with Ranging and RangingPhr values (in the DataRequestRangingDescriptor parameter) both set to TRUE ~~equal to ALL_RANGING~~. Upon receipt of a MCPS-DATA.request primitive with Ranging equal to TRUE ~~ALL_RANGING~~, RDEV shall generate ranging ~~timestamp~~ reports for all RFRAMEs after the transmit frame is transmitted. The ranging ~~timestamp~~ 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 6-48. 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 ~~Timestamp~~ 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 6-48, the first ranging ~~timestamp~~ report to the originator next higher layer is via parameters ~~shall come back as elements~~ of the MCPS-DATA.confirm primitive. The first ranging ~~timestamp~~ report to the recipient next higher layer is via parameters ~~shall come back as elements~~ of the MCPS-DATA.indication primitive. All subsequent ranging ~~timestamp~~ reports on either side of the link are via parameters ~~shall come back as elements~~ of MCPS-DATA.indication and MCPS-DATA.confirm primitives. The potential additional MCPS-DATA.indication primitives that may ~~would~~ be due to unexpected stray RFRAMEs are not shown in Figure 6-48 for simplicity. The timestamp reports due to any strays shall continue until ranging is disabled. The generation of ranging reports ~~reporting of timestamps~~ for a stream of stray RFRAMEs ~~"strays"~~ is the behavior that enables the RDEV to be used as an infrastructure RDEV ~~RDEVs~~ in OWR ~~one-way ranging~~ applications. OWR ~~One-way ranging~~ is described in "Applications of IEEE Std 802.15.4" [B3].

For non-TVWS RDEVs, the timestamp is defined in ~~15.7~~ 6.9.1.1. Use of nonzero TX and RX ranging counter ~~timestamp~~ reports is limited to RDEVs. Only devices that have *phyRanging* set to TRUE shall return a ranging ~~nonzero timestamp~~ report to a next higher layer.

For TVWS RDEVs, the Timestamp IE, 7.4.4.26, and the Timestamp Difference IE, 7.4.4.27, 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 "Applications of IEEE Std 802.15.4" [B3].

Insert new subclauses 6.9.6 to 6.9.11 after 6.9.5 as follows:

6.9.6 Ranging procedures

6.9.6.1 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 6.9.1.2 are defined in 6.9.6, 6.9.7, and 6.9.8. 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 RangingStsS1Fom parameter(s) of the MCPS-DATA.indication primitive.

6.9.6.2 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 6.9.1.2.2 and 6.9.1.2.3, 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. To ensure the integrity of this information transfer it is recommended to employ the secure private data communication capability of this standard.

6.9.6.3 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 7.4.4.45, requesting the ranging reply time information, and with Ranging Control Information field set according to Table 7-52k.

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 7.4.4.46), carried by a subsequent message.

Figure 6-48a 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 6.9.1.2.2.

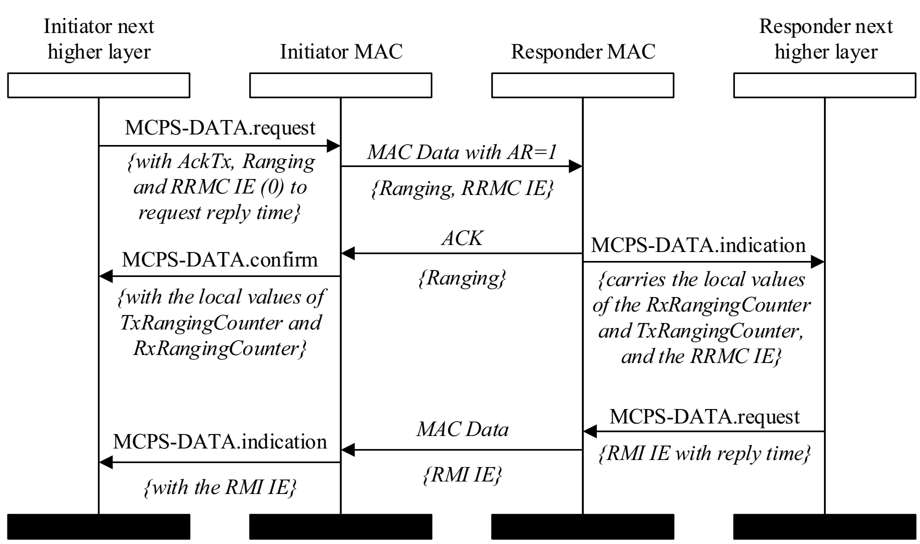

Figure 6-48a—Message sequence chart for SS-TWR with deferred reply time result

6.9.6.4 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 7.4.4.45) requesting the ranging reply time information, and with the Ranging Control Information field set according to Table 7-52k. 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 7.4.4.35. 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 6-47a and its associated description in 6.9.1.2.2 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 7.4.4.49 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 6-48b 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 6.9.1.2.2.

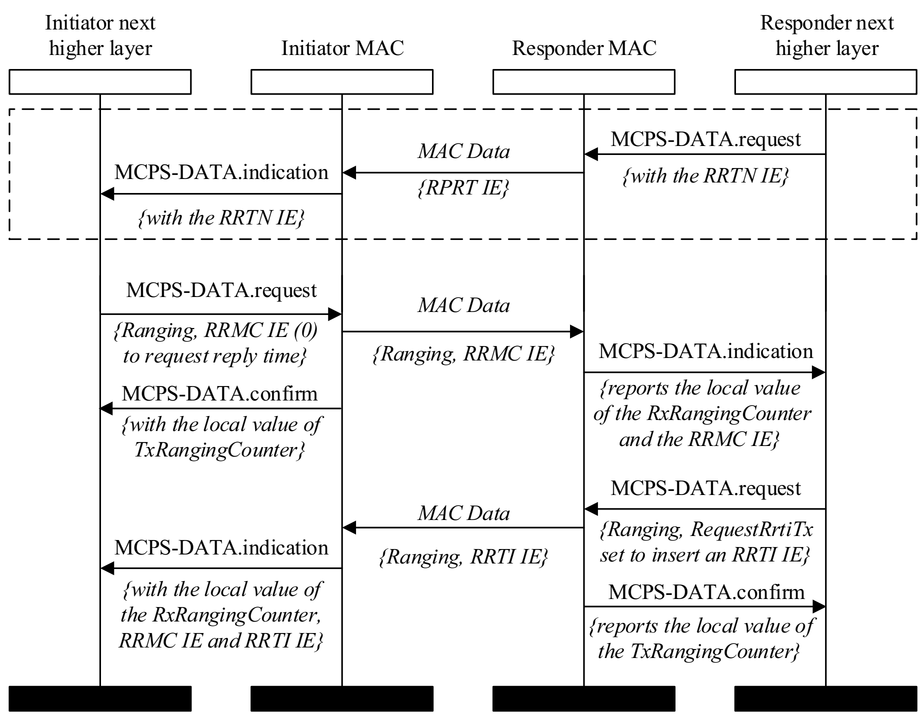

Figure 6-48b—Message sequence chart for SS-TWR with embedded reply time

6.9.6.5 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 6-47a, 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 6-48c shows an example message sequence chart for such a ranging exchange.

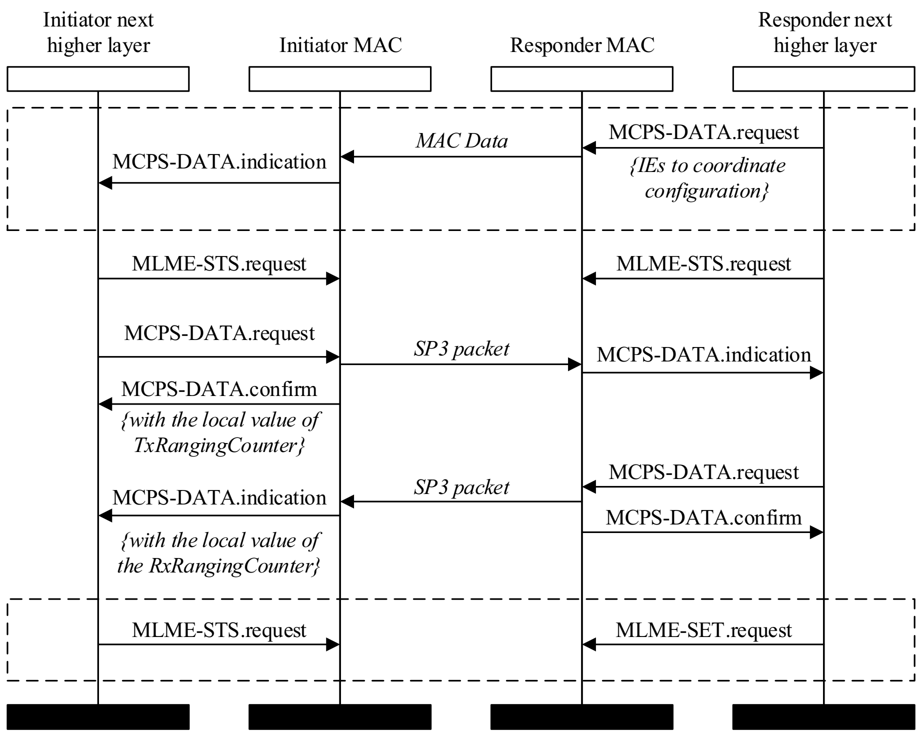

Figure 6-48c—Message sequence chart for SS-TWR using SP3 packets

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 7.4.4.49) 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 *phyHrpUwbStsKey*, *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 6.9.1.2.2.

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 6-48c.

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 6.9.8.4.

6.9.6.6 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 7.4.4.45) with the Ranging Control Information field set according to Table 7-52k. 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 7-52k 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 7.4.4.46). Figure 6-48d 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 6.9.1.2.3. 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.

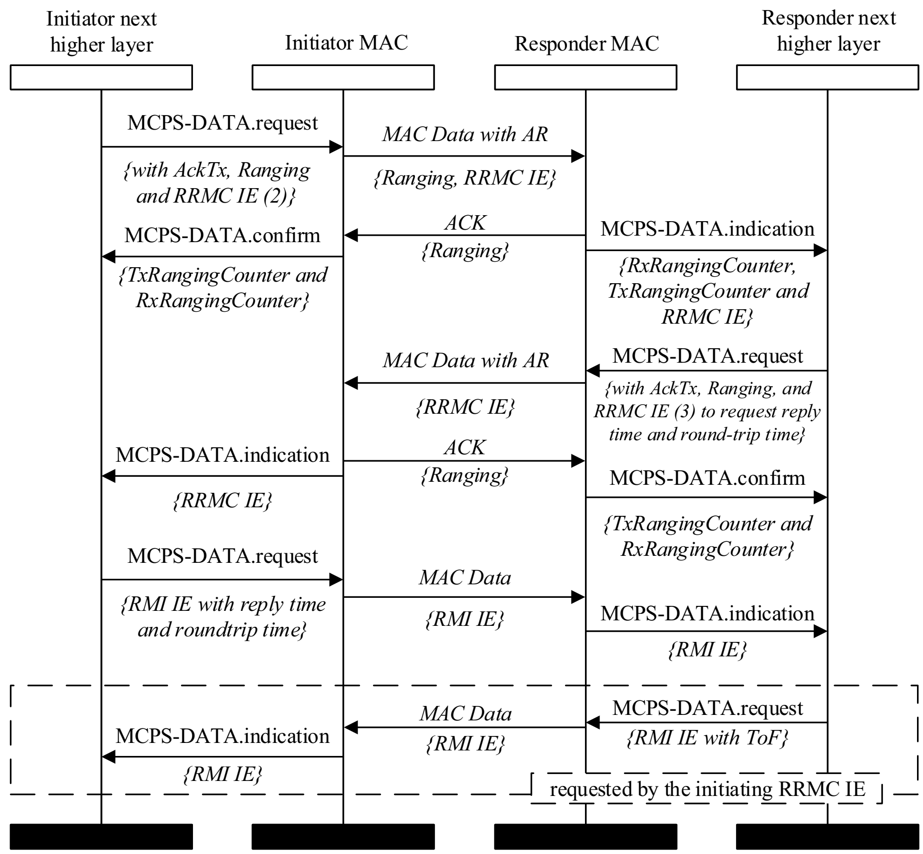

Figure 6-48d—Message sequence chart for DS-TWR with deferred reply time result

6.9.6.7 Ranging procedure for DS-TWR with embedded ranging time information

To achieve the three-message DS-TWR exchange described in Figure 6-47c 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 6-48e, the DS-TWR is initiated by an RFRAME carrying an RRMC IE (described in 7.4.4.45) with its Ranging Control Information field set according to Table 7-52k, 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 RFRAME carrying an RRMC IE with control field set according to Table 7-52k 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 RFRAME carrying the first round-trip time measurement in an RMI IE (described in 7.4.4.46) and the reply time of this second round-trip time measurement in an RRTI IE (as described in 7.4.4.35).

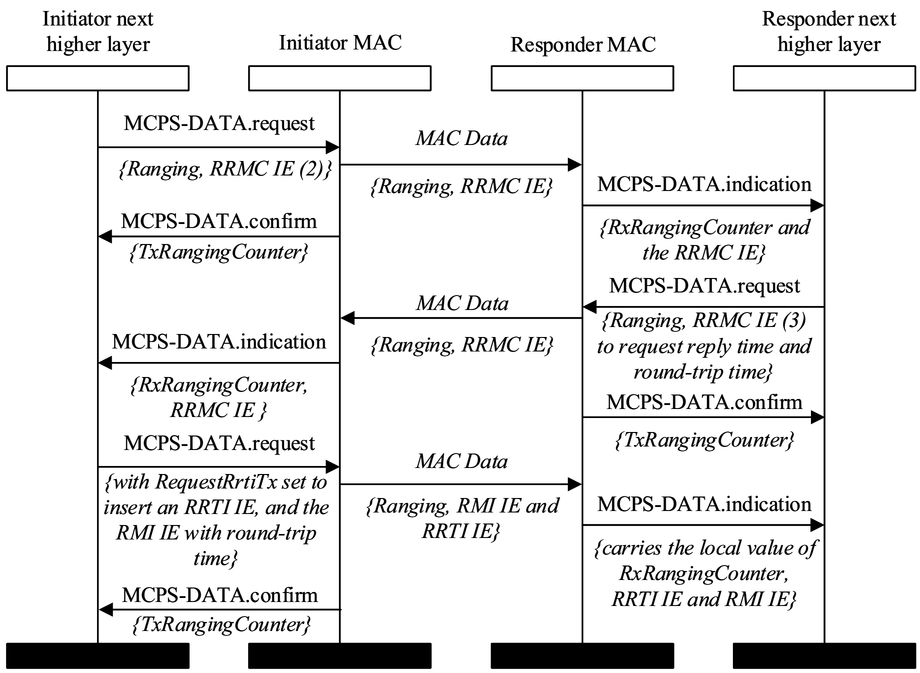

Figure 6-48e—Message sequence chart for DS-TWR with three messages

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 6.9.1.2.3. 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 6-48d.

6.9.6.8 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 key 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 Key and Data IE (RSKD IE) as described in 7.4.4.42. The counter value within the RSKD IE can relate to the current packet or a future one, as is indicated by the CP field of the IE. The higher layer is responsible for using the received RSKD IE information to configure the STS seed, (via *phyHrpUwbStsKey*, *phyHrpUwbStsVUpper96*, and *phyHrpUwbStsVCounter* PIB attributes), appropriately for its future packet transmissions and receptions. A header IE version of the RSKD IE is also defined, in 7.4.2.20, to facilitate synchronization of STS generators using information sent in the clear while accompanied by secured payload IEs and data.

When receiving a received frame that contains an RSKD IE header IE, it is intended that the IE is delivered to the next higher layer to allow it to set the *phyHrpUwbStsKey*, *phyHrpUwbStsVUpper96*, and *phyHrpUwbStsVCounter* attributes appropriately for STS generation. If a frame containing an RSKD 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 RSKD 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 6.9.4, 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 7.4.4.48).

6.9.6.9 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 RFRAME, 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 6-48f. 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 6-48f—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 6-4e.

The USSID Length field specifies the number of octets in the USSID field. The valid range for USSID Length shall be 0 to 16.

Table 6-4e—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.
3	MAC Payload field contains a Mifare Desfire® command or response.
4	MAC Payload field contains an Information field as defined by JIS X 6319-4.
5–7	Reserved.

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 6-4f. 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 6-4f—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 6-48g 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 6-48g 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 6-48h.

Octets: 5–16
AID

Figure 6-48g—Format of USSID field when carrying an AID

The AID is an Application Identifier as defined in ISO/IEC 7816-5.

Octets: 2
SC

Figure 6-48h—Format of USSID field when carrying an SC

The SC is a system code as defined by JIS X 6319-4.

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 [B7b]. 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.

6.9.7 Multi-node ranging

6.9.7.1 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 7.4.4.36. The RCM can be used to convey ranging parameters to control and configure aspects of the ranging procedure(s) such as the time-slot structure shown in Figure 6-48j, the ranging methods specified in 6.9.1.2, and the STS packet configuration as specified in 15.2.

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 controllee can be an initiator.
— Responder: An ERDEV that responds to the ranging initiation message received from the initiator.

These terms are illustrated in Figure 6-48i.

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 controlee refer to those entities' next higher layer being informed of the event or taking the action being described.

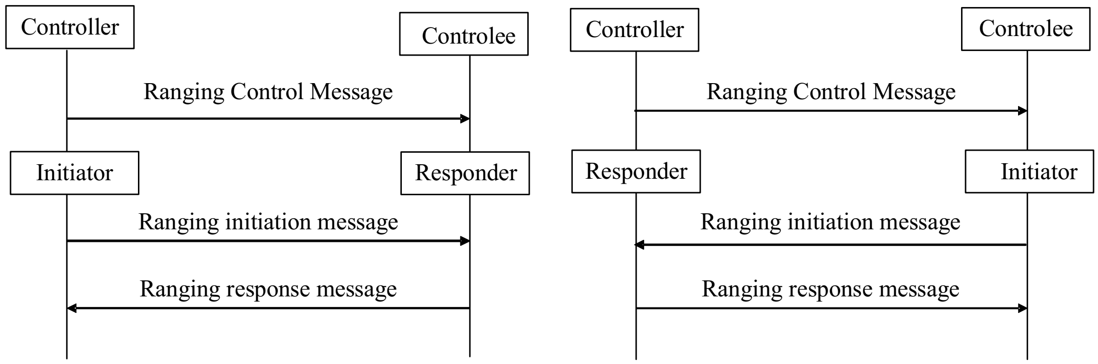

Figure 6-48i—Ranging controller, controlee, initiator, and responder

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 7.4.4.36. The first type is time-scheduled ranging in which the controller knows the identities of all controlees 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 controlees, and hence the ERDEVs contend with each other. Note that 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 7.4.4.44 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 RDM 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 7.4.4.40, is used to specify different phases (see 6.9.7.2) for initiators and responders to contend, which can be conveyed in the RCM (in addition to the ARC IE). To ensure the 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 7.4.4.41, in the RCM. Furthermore, if the controller knows the identities of the controlees, the RDM IE can be used to allocate ranging roles, that is initiator or responder, among ERDEVs.

6.9.7.2 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 RFRAME. Figure 6-48j 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.

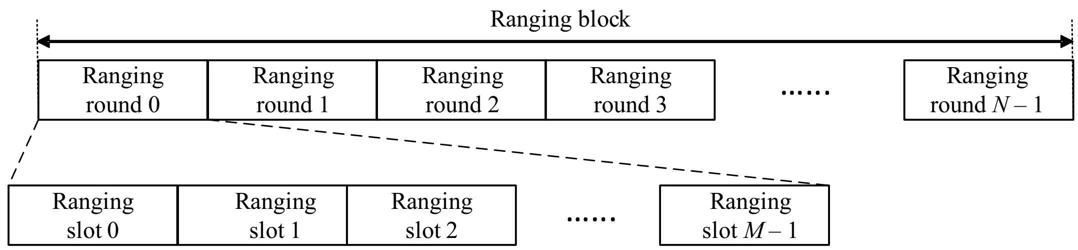

Figure 6-48j—Illustration of ranging block, ranging round, and ranging slot

The time unit used in specifying the duration of ranging block, ranging round, and ranging slot is the RSTU as specified in 6.9.1.5. 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 6.9.7.3.2, 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 6.9.7.4 to 6.9.7.8, or OWR may be used as described in 6.9.1.2.5. As shown in Figure 6-48k, 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.

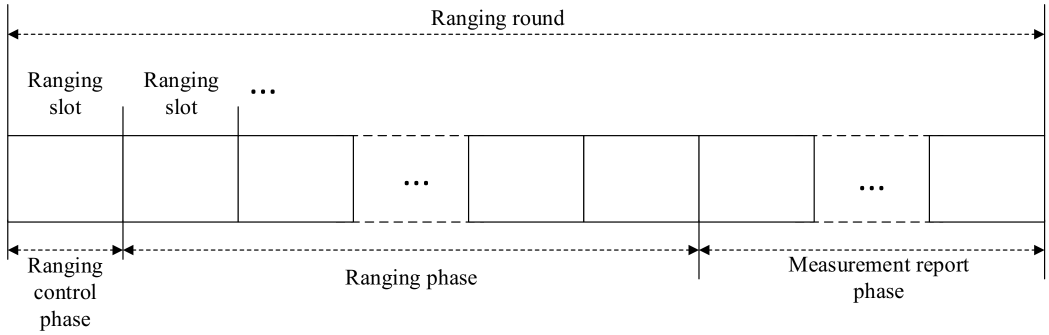

Figure 6-48k—An example of phases in a ranging round

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 7.4.4.40). 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 7.4.4.44), or by an out-of-band mechanism.

In Figure 6-48l, 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.

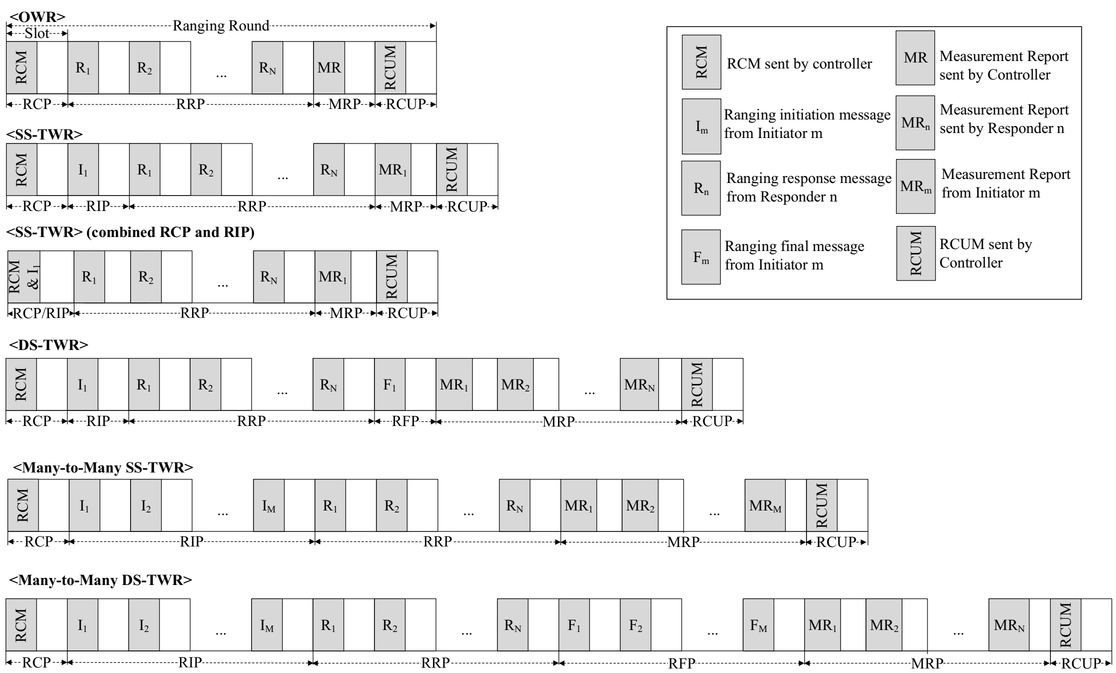

Figure 6-48l—Example timing diagrams for some different multi-device ranging use cases

For ranging with the SP3 format packets, described in 15.2, 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 controlees participating in the ranging exchange. The controller may send its request in-band as part of the RCM, for example using SP3 Ranging Request Reports IE (SRRR IE) described in 7.4.4.47, 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 7.4.4.44). 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 6-48m. 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 6-48m, 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 ≥ K × 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 + Packet length < (N + 1) × Slot length.

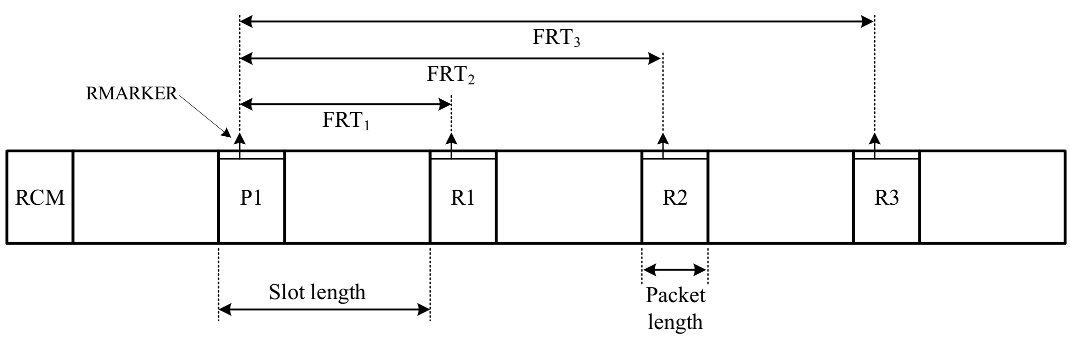

Figure 6-48m—Example ranging round with fixed reply time

The requested fixed reply times can be exchanged via the RRTN IE (described in 7.4.4.49) before the ranging starts or via an out-of-band mechanism.

6.9.7.3 Ranging modes

6.9.7.3.1 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 7.4.4.36.

6.9.7.3.2 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 7.4.4.37.

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 7.4.4.36) 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 controlee(s) using an RIU IE described in 7.4.4.37. The RIU IE can be included in the RCM, RCUM, and RIUM. Upon reception of the RIU IE, each controlee 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 controlee can request a change to the current ranging configuration by sending a change request with the RCR IE (described in 7.4.4.43), to the controller. The RCR IE can be transmitted along with various IEs to indicate the preferred parameter settings of a controlee, such as the ARC IE (described in 7.4.4.36), the RIU IE (described in 7.4.4.37), the RCPCS IE (described in 7.4.4.48), and the RSKD IE (described in 7.4.4.42). 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 controlee. 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 6-48n, 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 6-48n shows a time diagram example of interval-based mode with one ranging round per ranging block.

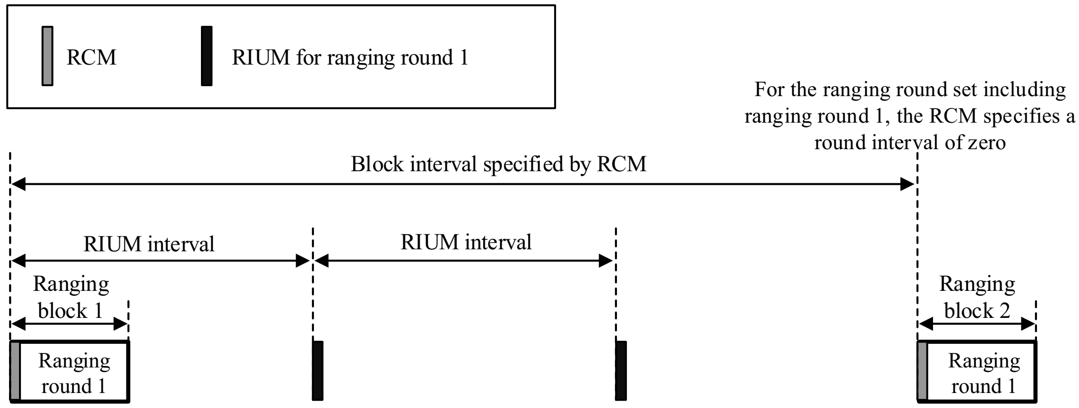

Figure 6-48n—Time diagram for an example of interval-based mode with one ranging round per ranging block

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 7.4.4.36) is supplied to the next higher layer of the controlee 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 6-48o shows a time diagram for an example of interval-based mode with two ranging rounds per ranging block.

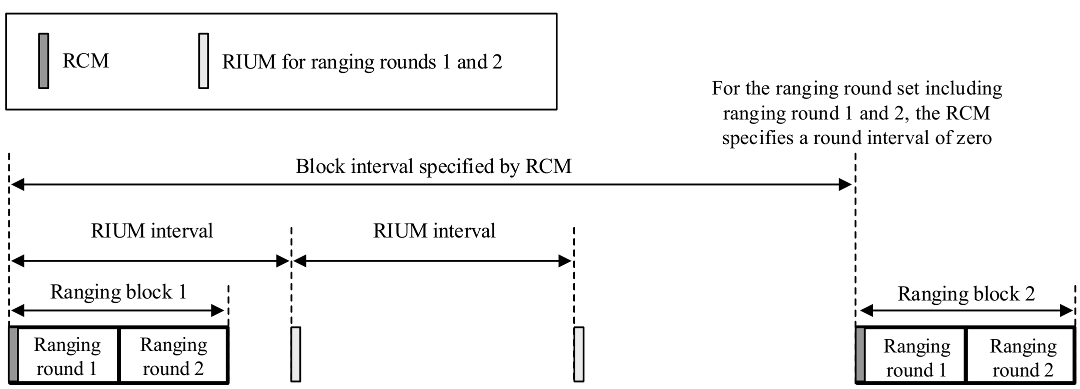

Figure 6-48o—Time diagram for an example of interval-based mode with two ranging rounds per ranging block

In ranging round one of the first ranging block, the controller transmits an RCM that includes an ARC IE (as described in 7.4.4.36) and an RIU IE for ranging rounds one and two. Upon reception of the RCM, the controlees 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. 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 6-48p shows a time diagram for an example of interval-based mode with two ranging round sets per ranging block.

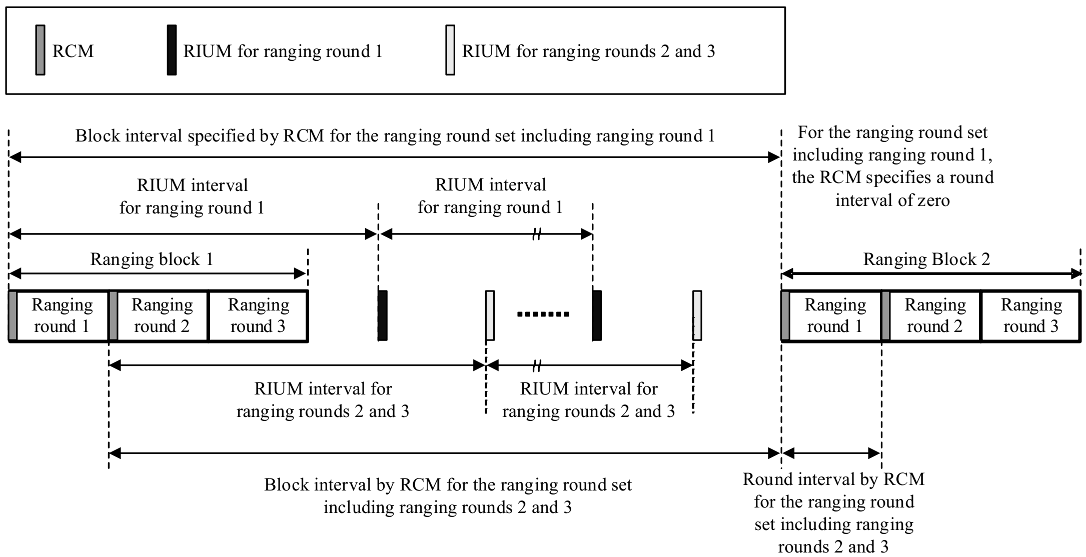

Figure 6-48p—Time diagram for an example of interval-based mode with two ranging round sets per ranging block

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 7.4.4.36) and the RIU IE. Upon reception of the RCM, the controlees 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 controlee is not aware of the interval timings, it may recover by continuing to listen to the channel to receive a subsequent RCM.

If a controlee has information for the previous intervals updated by the previous RCM and fails to receive RCM, RCUM, or RIUM with updated intervals, the controlee 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 controlee. If the controlee receives the RIUM, it can receive the RCM transmitted by the controller and send its RFRAME in the ranging round with the updated intervals. The controller may stop transmitting the RIUM if the RFRAME from the controlee is successfully received.

RCM Timing Window (RTW) operation is optionally specified by the RIU IE as described in 7.4.4.37. 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 controlee has to enable its receiver during the RTW in order to receive the RCM.

The controller and the controlee 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 controlee waits during the RTW to receive the RCM.

Figure 6-48q shows a timing diagram for an example of the RCM transmission with the RTW. RCMs are transmitted at random time within the RTW.

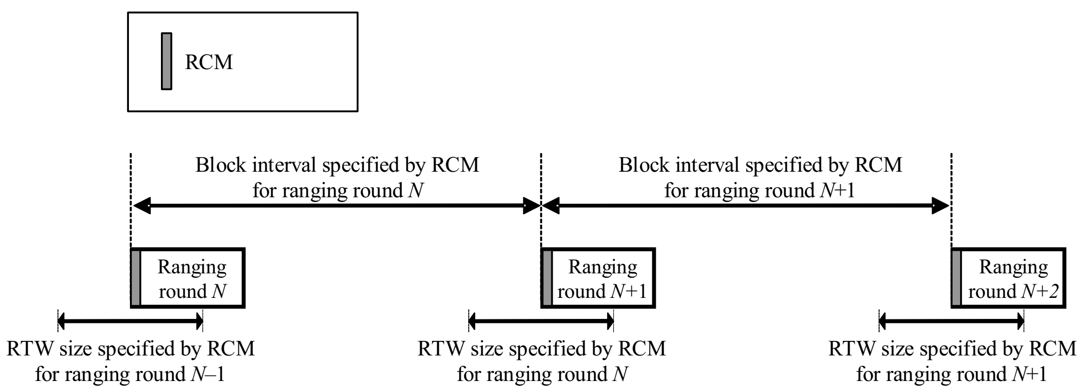

Figure 6-48q—Time diagram for an example of RCM transmission with RTW

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 same. If a controlee fails to receive the RCM of ranging round $N + 1$, the controlee can receive the RCM of ranging round $N + 2$ transmitted at random time within the RTW of ranging round $N + 2$.

6.9.7.3.3 Block-based mode

Block-based mode uses a structured timeline where the ranging block structure, as defined in 6.9.7.2, is periodic by default. Figure 6-48r 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 7.4.4.36).

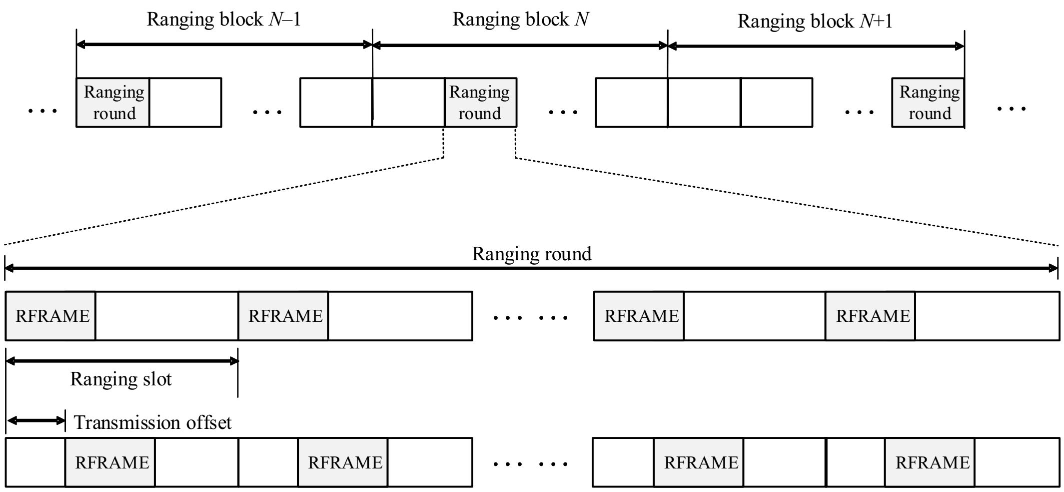

Figure 6-48r—Time diagram for an example of block-based mode

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 7.4.4.39, 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 7.4.4.38 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 controlee, 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 6-48s shows an example of ranging rounds with different transmission offsets.

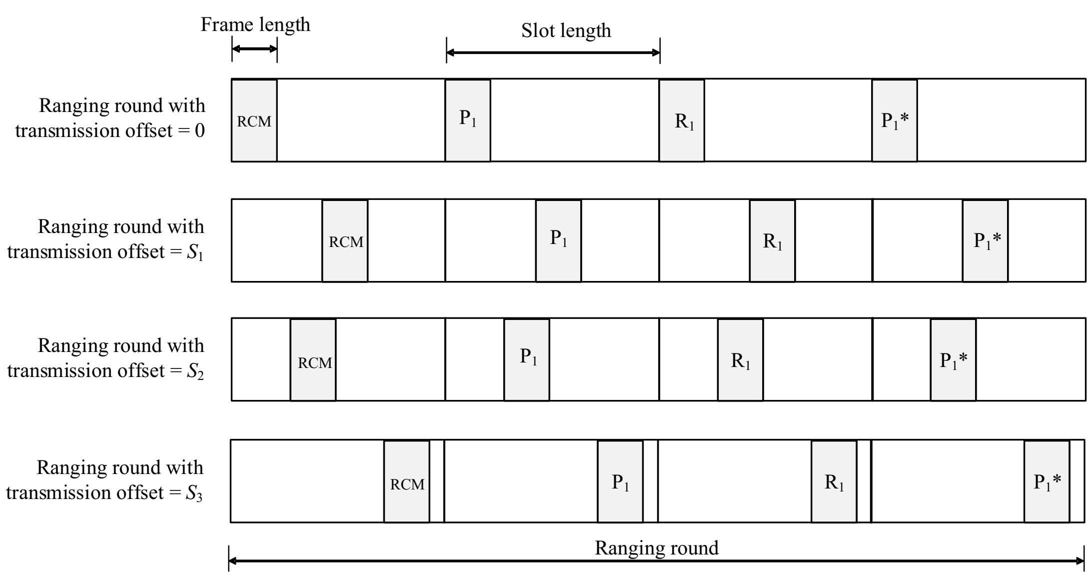

Figure 6-48s—Ranging rounds with different transmission offset

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 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 ≠ m). Figure 6-48t 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.

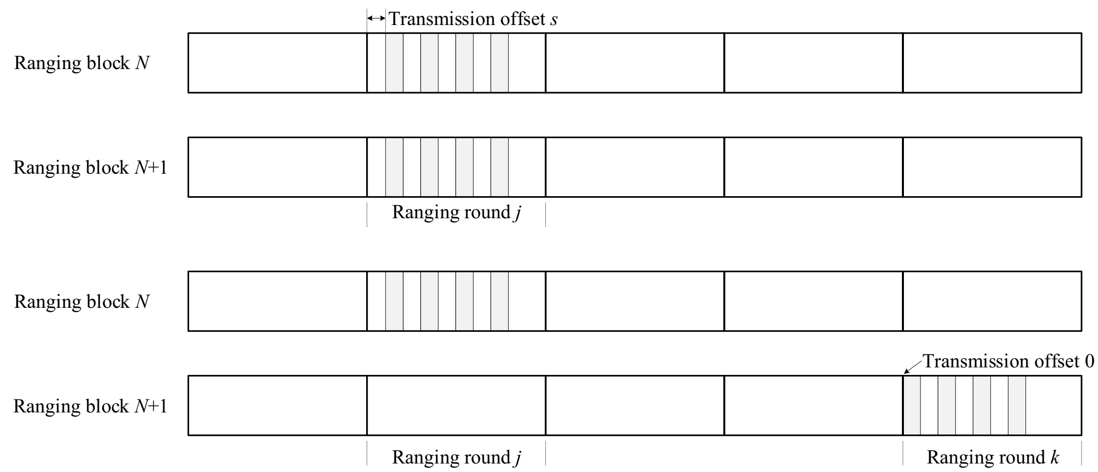

Figure 6-48t—Illustration of transmission offset and round hopping

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 7.4.4.36) and the RR IE (described as defined in 7.4.4.38). 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 controlee next higher layer is responsible for using the indicated ranging round and transmission offset in the subsequent ranging block. If the controlee 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 controlee 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.

6.9.7.3.4 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 6-48u.

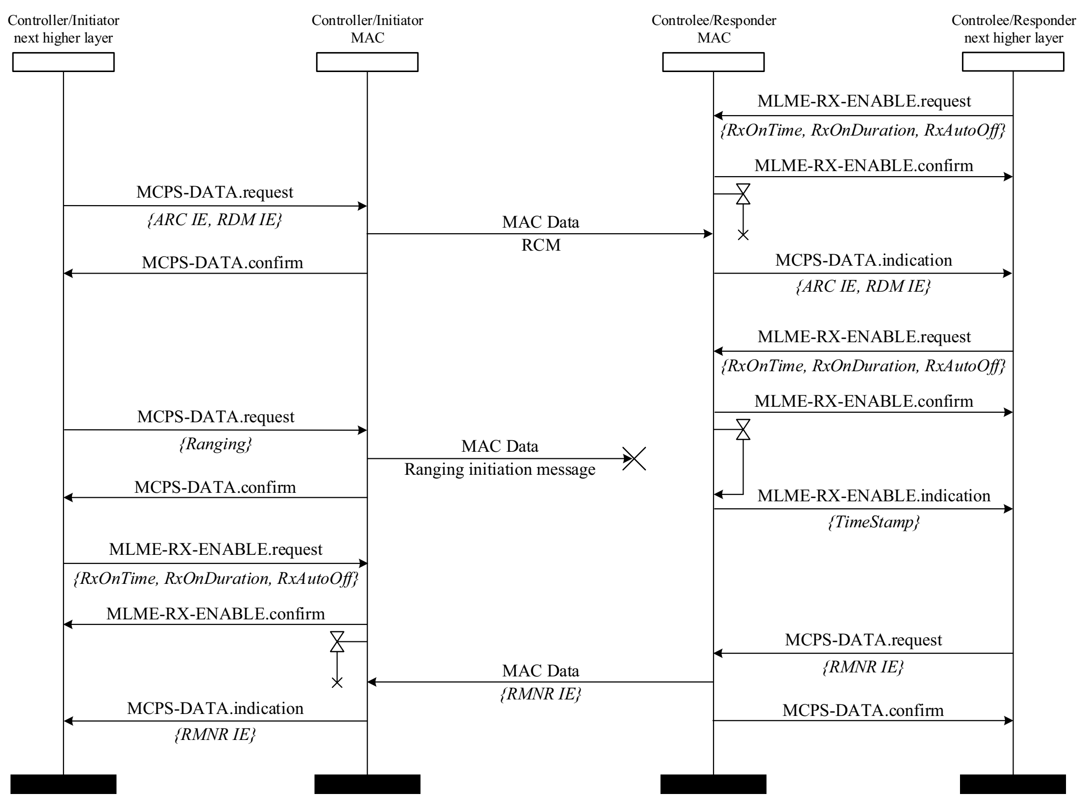

Figure 6-48u—Message sequence chart illustrating MLME-RX-ENABLE.indication use

6.9.7.4 Ranging Procedure for one-to-many SS-TWR

For one-to-many SS-TWR, as shown Figure 6-48v, the example ranging exchange is started by the initiator, where the RRMC IE as described in 7.4.4.45 is embedded in the ranging initiation message broadcast to multiple responders.

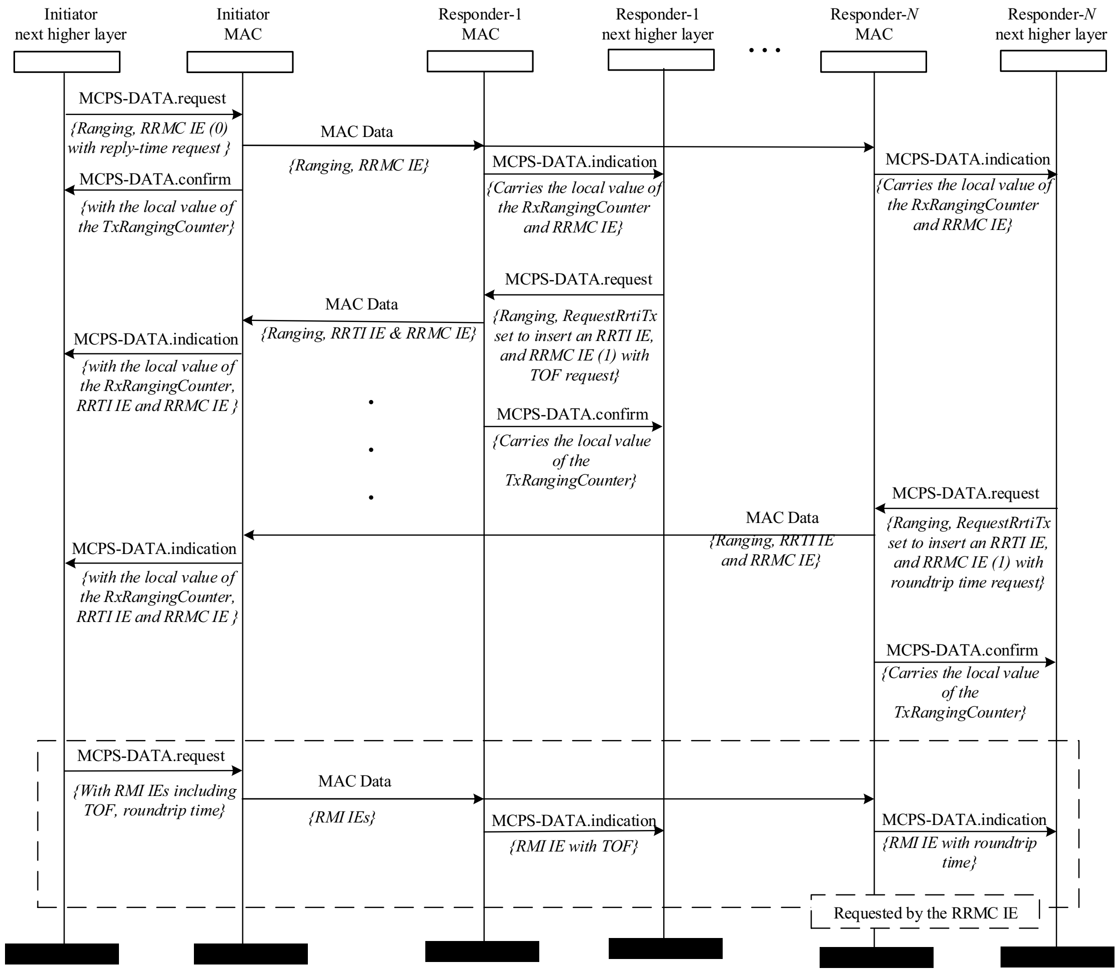

Figure 6-48v—Message sequence chart for one-to-many SS-TWR

The Ranging Control Information field of the RRMC IE is set to zero according to Table 7-52k, indicated by the designation RRMC IE (0) in Figure 6-48v. 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 RequestRrtiTxList parameter set to insert the RRTI IE (described in 7.4.4.35) and to convey the RRMC IE with Ranging Control Information field set to one (as per Table 7-52k) and indicated by the designation RRMC IE (1) in Figure 6-48v. The response RFRAMEs are unicast to the initiator.

For the multi-node ranging based on scheduling (as described in 6.9.7.2), 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 6-48v 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 6-48v, 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 7.4.4.46) to fulfill the measurement reports, where the Address field of the RMI IE distinguishes which node the reported measurements relate to. 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.

6.9.7.5 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 7.4.4.45) selecting the responders and with its Ranging Control Information field set to two (as per Table 7-52k) as indicated by the designation RRMC IE (2) in Figure 6-48w.

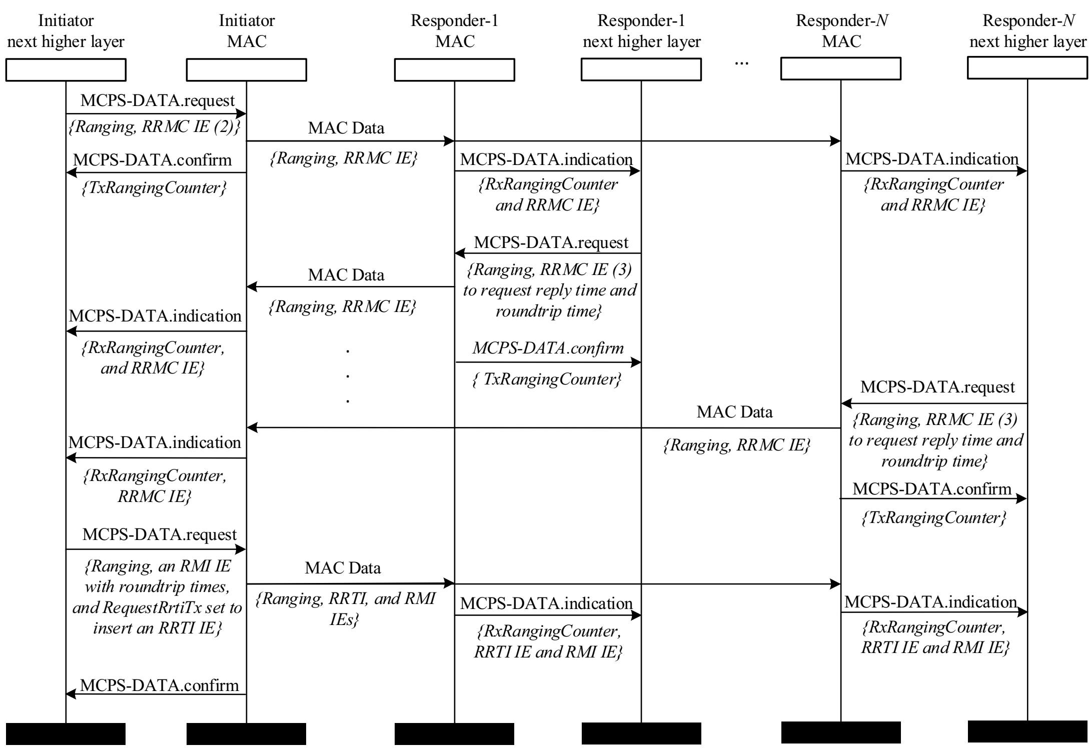

Figure 6-48w—Message sequence chart for one-to-many DS-TWR: no request of ranging result from the initiator

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 6-48w), with the Ranging Control Information field set to three (as per Table 7-52k), 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 6.9.7.4), 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 7.4.4.46) to report the round-trip times, and an RRTI IE (described in 7.4.4.35) to report the reply times.

Figure 6-48w 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 6-48w, 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 6-48x illustrates the message sequence chart for one-to-many DS-TWR when the Deferred Mode field is one in the ARC IE (described in 7.4.4.36). Therefore, the initiator sends the first round time and second reply time to the responders using RMI IEs (described in 7.4.4.46) in a deferred data frame (with the Deferred Mode field of the RMI IE set to one).

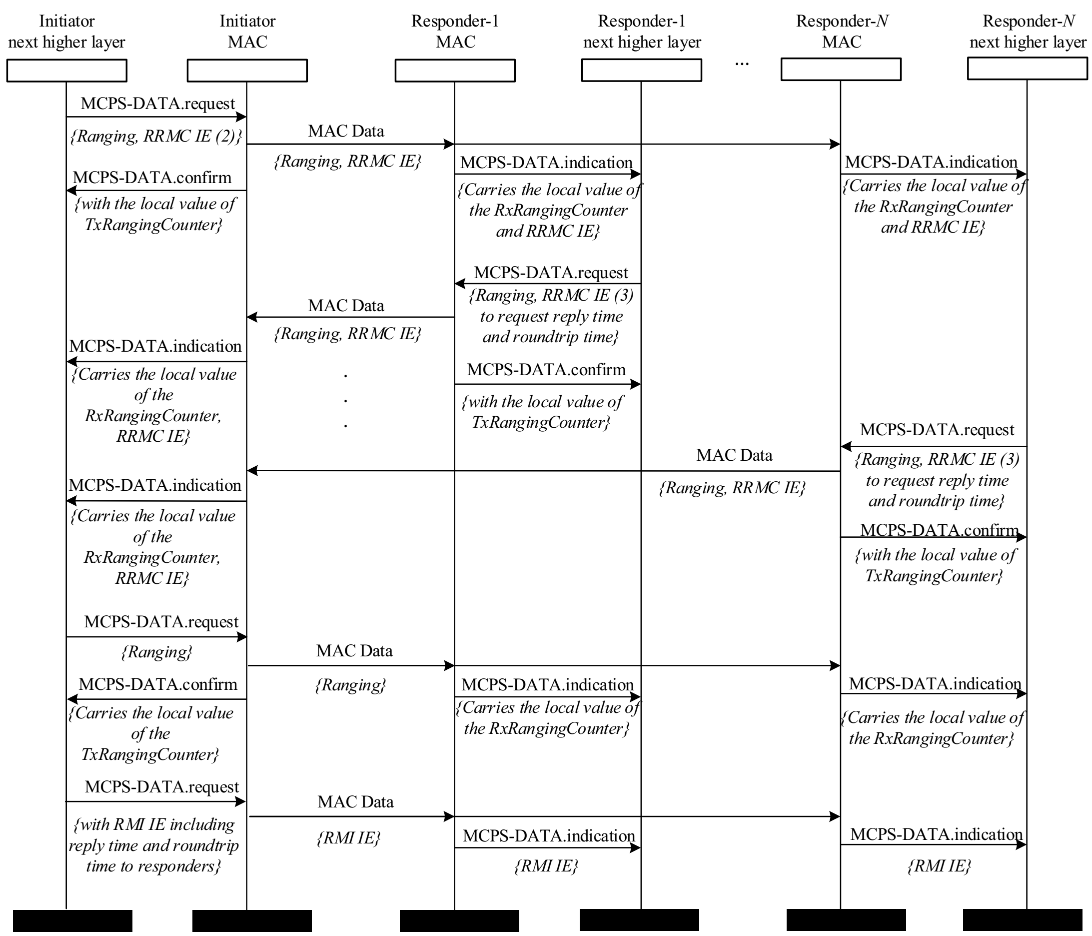

Figure 6-48x—Message sequence chart for one-to-many DS-TWR: no request of ranging result from the initiator with deferred mode

In Figure 6-48y, 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 RequestRrtiTxList 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 RequestRrtiTxList 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.

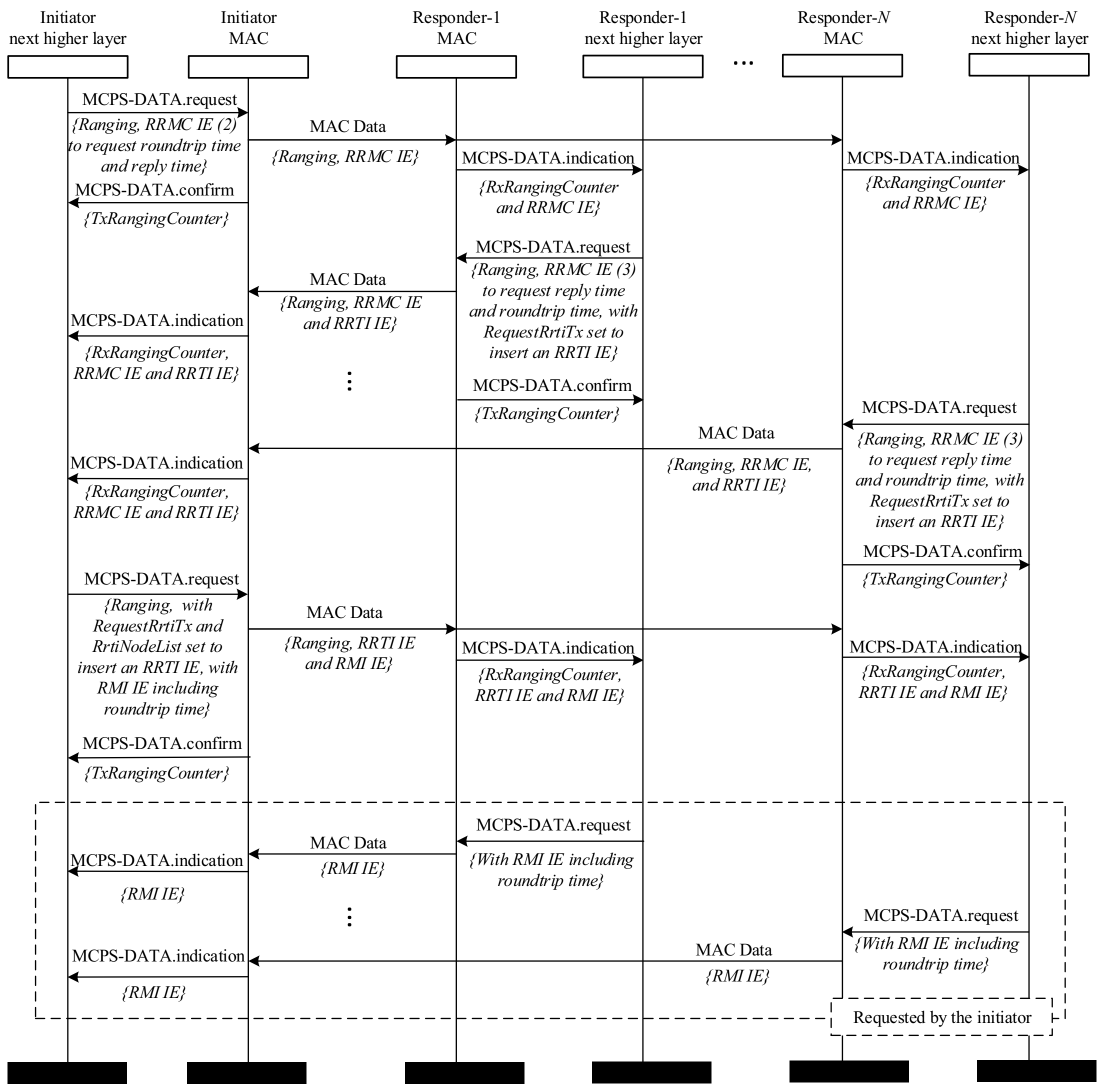

Figure 6-48y—Message sequence chart for one-to-many DS-TWR: request of the first reply time and second round-trip time from the initiator

In Figure 6-48z, 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.

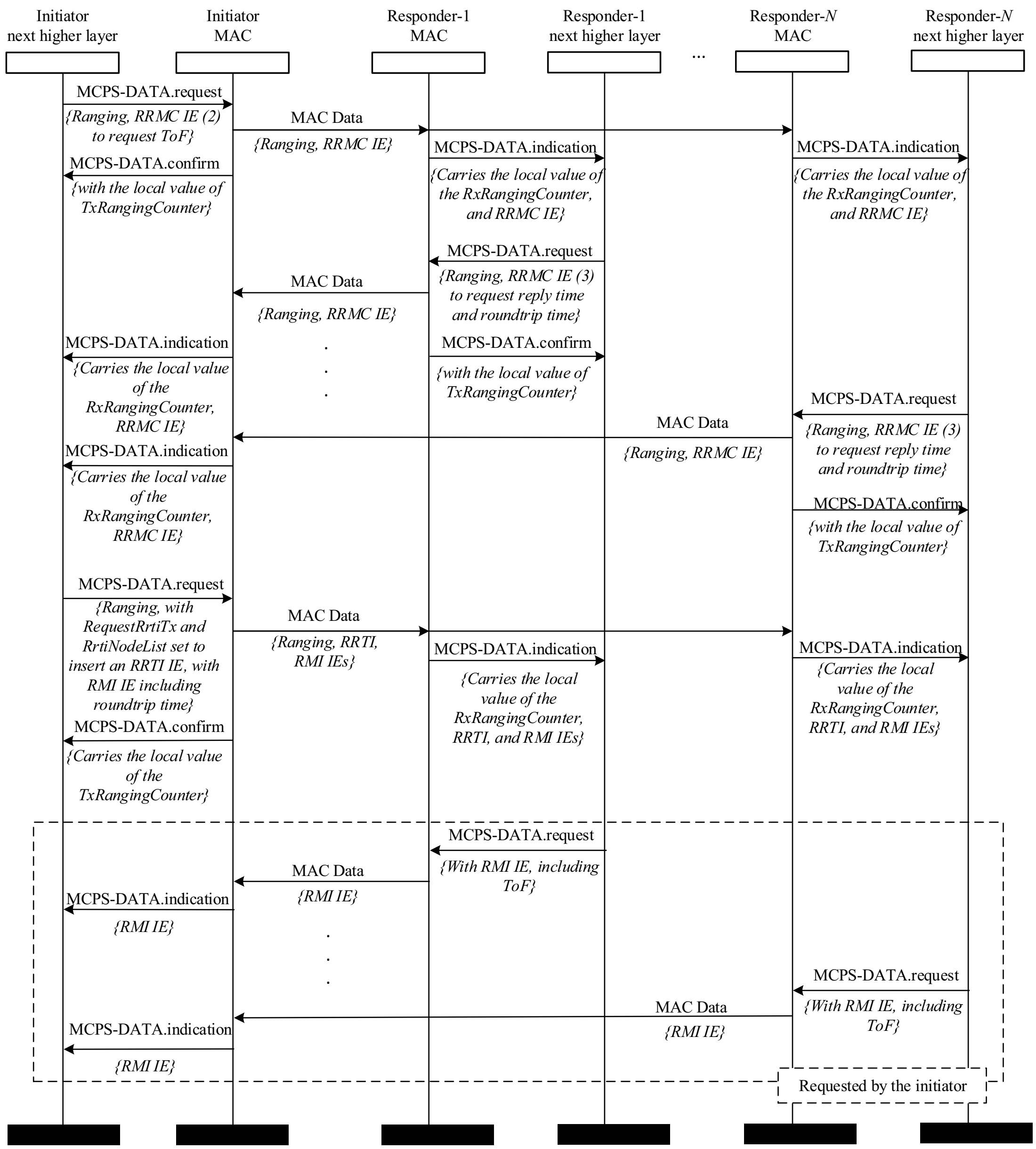

Figure 6-48z—Message sequence chart for one-to-many DS-TWR: request of ranging result from the initiator

6.9.7.6 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 7.4.4.45), 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 RFRAME using the MCPS-DATA.request primitive with the

RequestRrtiTxList parameter set to insert an RRTI IE (described in 7.4.4.35) for each initiator. The response RFRAMEs are sent to the initiators in the ranging response phase based on time-scheduling or contention determined via the ranging configuration.

Figure 6-48z1 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 ensure that each required response is supplied 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 7.4.4.36) and RDM IE (described in 7.4.4.44). In Figure 6-48z1, the responders do not request the ranging results. However, as in Figure 6-48v, the responders can request ranging results from the initiators, which would require an additional Data frame to be transmitted by each initiator.

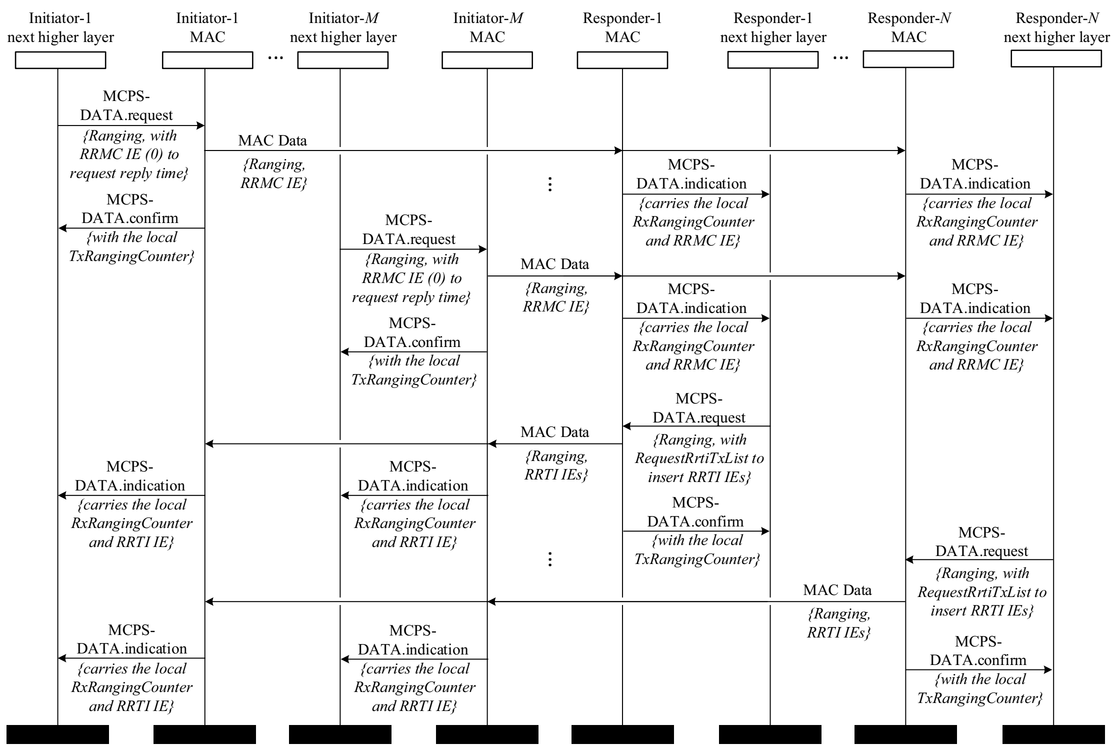

Figure 6-48z1—Message sequence chart for M2M SS-TWR

6.9.7.7 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 7.4.4.45). The Ranging Control Information field in the RRMC IE is set to two, which is indicated by the designation RRMC IE (2) in Figure 6-48z2.

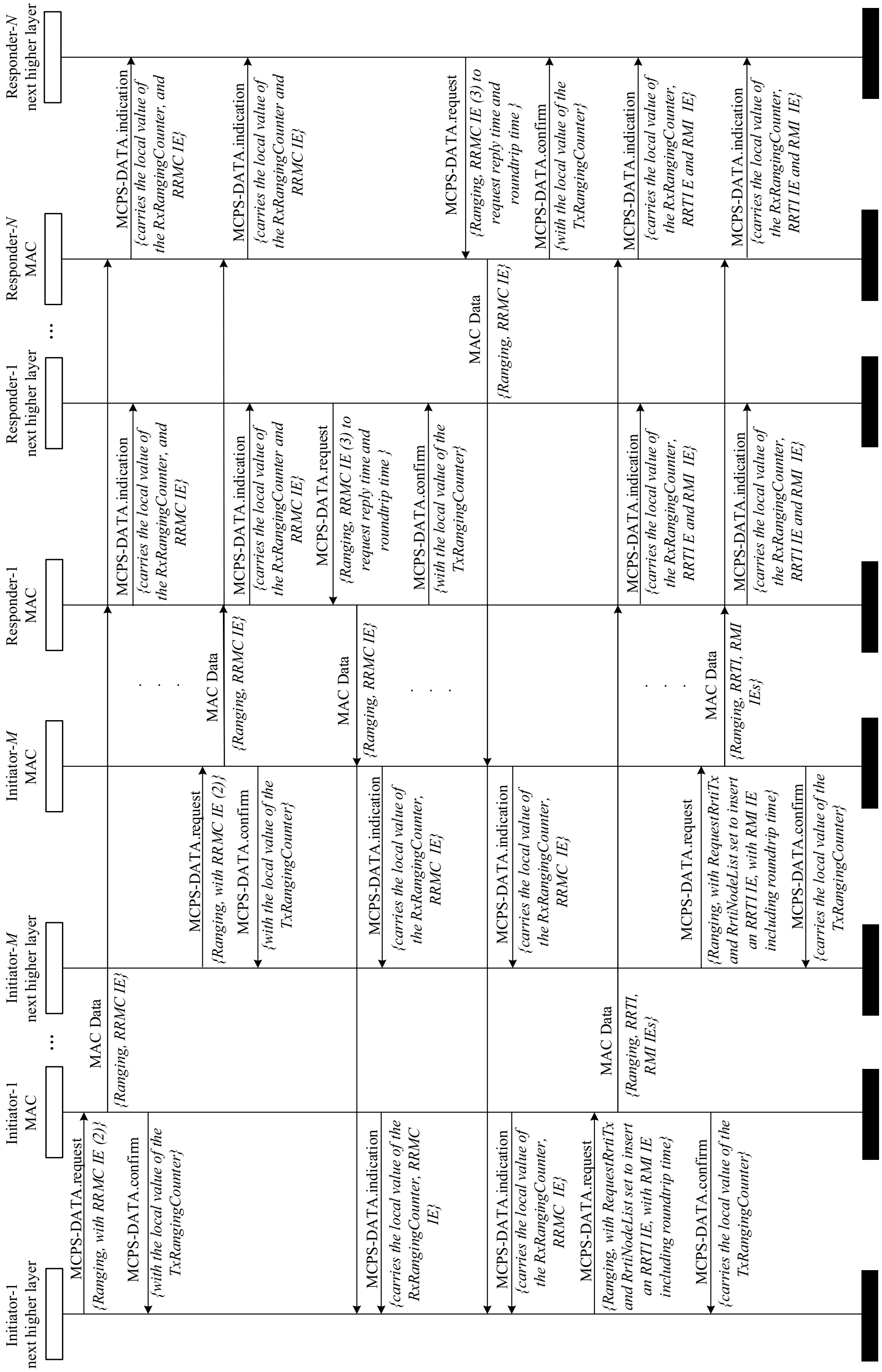

Figure 6-48z2—Message sequence chart for M2M DS-TWR

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 6-48z2, 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 RFRAME, which includes an RRTI IE (as described in 7.4.4.35) to report the reply time, and an RMI IE (as described in 7.4.4.46) to report the round-trip time.

Figure 6-48z2 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 RFRAME from an initiator, each responder's next higher layer has sufficient information to calculate its TOF to the initiator.

6.9.7.8 Ranging Procedures with SP3 format packets

6.9.7.8.1 Introduction

In this subclause, the examples of SP3 packet based ranging procedures are illustrated by message sequence charts in Figure 6-48z3 and Figure 6-48z4, 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.

6.9.7.8.2 Ranging Procedure for multi-node SS-TWR with SP3 packets

Figure 6-48z3 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 controlees. 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 7.4.4.47) 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 7.4.4.44) in the RCM is used to convey the assignment of time slots and device roles in a ranging round. The ARC IE (described in 7.4.4.36) 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 RSKD IE (described in 7.4.4.42) 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 *phyHrpUwbStsKey*, *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 6-48z3 and Figure 6-48z4 are based on the time structure shown in Figure 6-48k, where the ranging controller adds the SRRR IE (described in 7.4.4.47) 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 RFRAME 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.

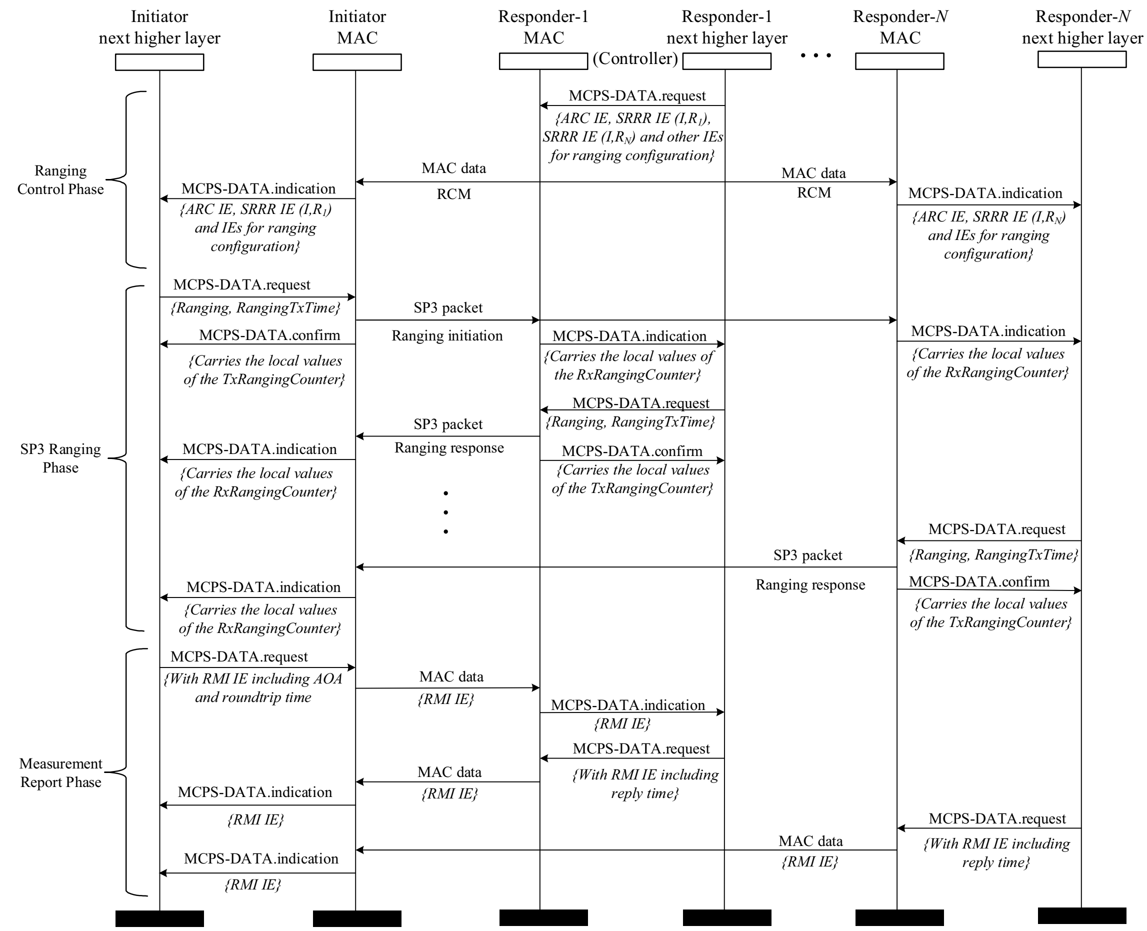

Figure 6-48z3—Message sequence chart for SP3 one-to-many SS-TWR

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 7.4.4.36), 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 Figure 6-48z4, the initiator conveys the AOA and round-trip time to Responder-1 using the RMI IE (described in 7.4.4.46) 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.

6.9.7.8.3 Ranging Procedure for multi-node DS-TWR with SP3 packets

Figure 6-48z4 illustrates an example of one-to-many DS-TWR with SP3 packets, which is similar to Figure 6-48z3. 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 7.4.4.47). After the SP3 ranging, ERDEVs are scheduled to send their reports with the requested information using RMI IEs (described in 7.4.4.46). 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.

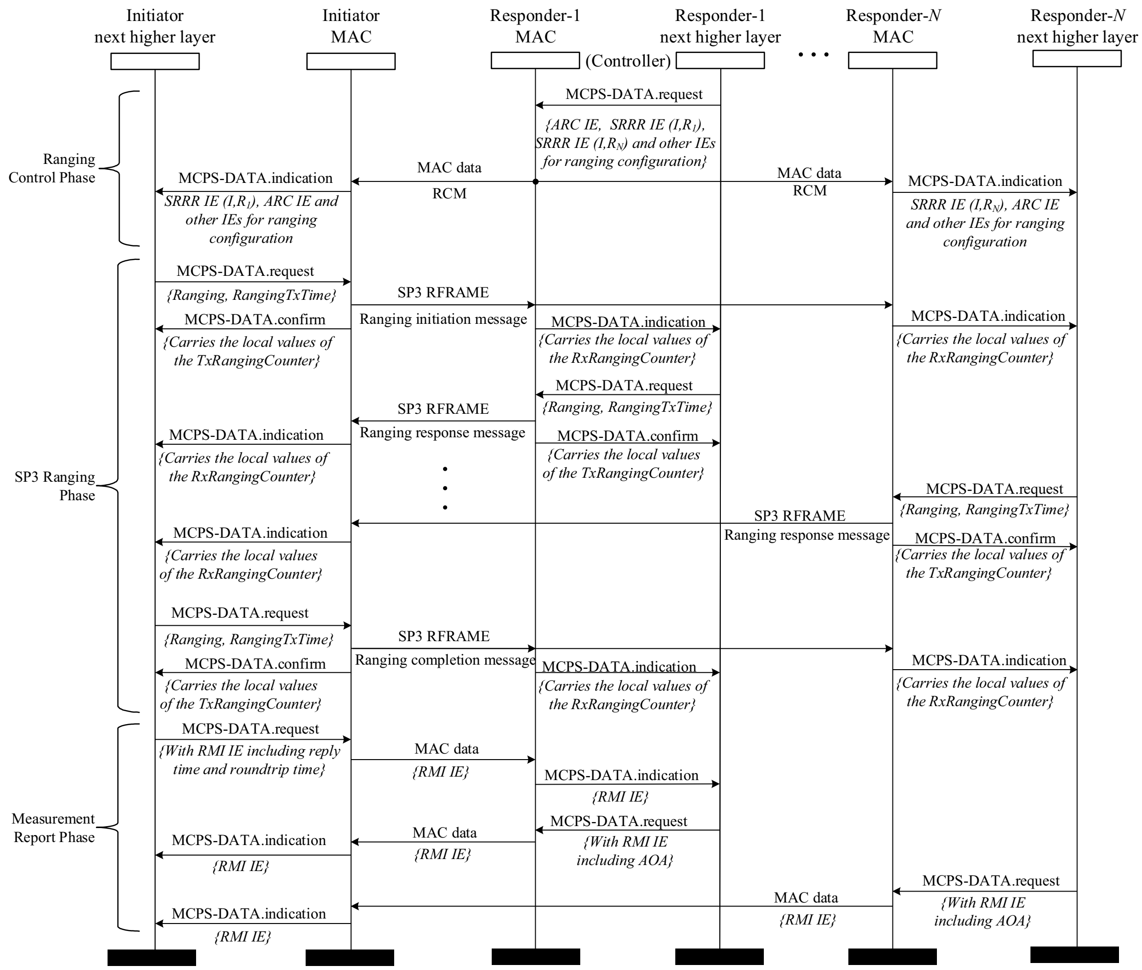

Figure 6-48z4—Message sequence chart for SP3 one-to-many DS-TWR

6.9.8 Authenticated challenge-response ranging

6.9.8.1 Overview

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 MAC command frame defined in 7.5.27 and the Ranging Prover MAC command frame defined in 7.5.28. 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 8.3.7 and 8.3.8, 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” [B20a].

The MCPS-RANGING-VERIFIER.request and MCPS-RANGING-PROVER.request primitives each include a SecurityLevel 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 6-48z5 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.

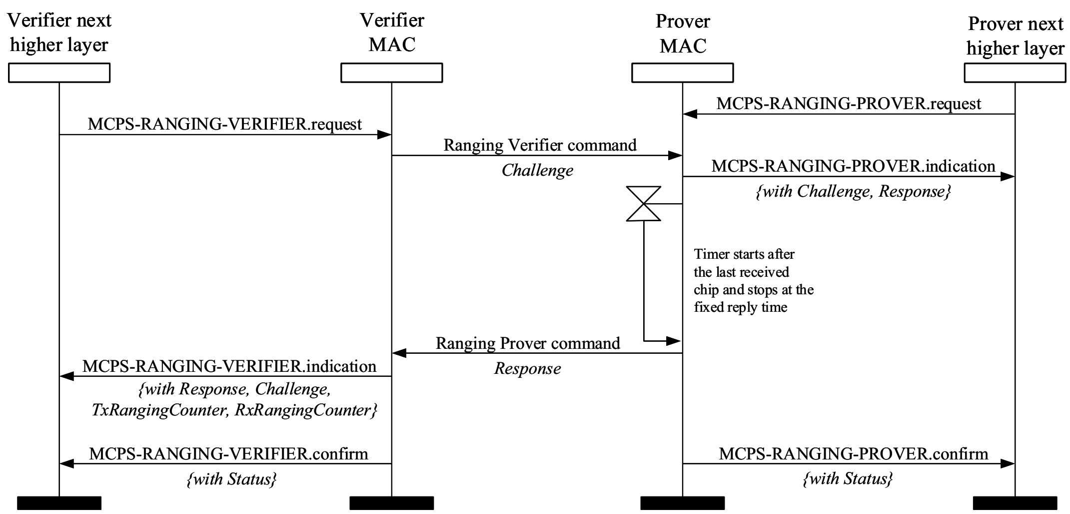

Figure 6-48z5—Message sequence chart for ACRR with fixed reply time

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 11-2. For the LRP-ERDEV, the fixed reply time is specified in 18.8.

The challenge and response data as well as other configuration parameters depend on the ACRR mode and are described in 6.9.8.4 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 6-48z6.

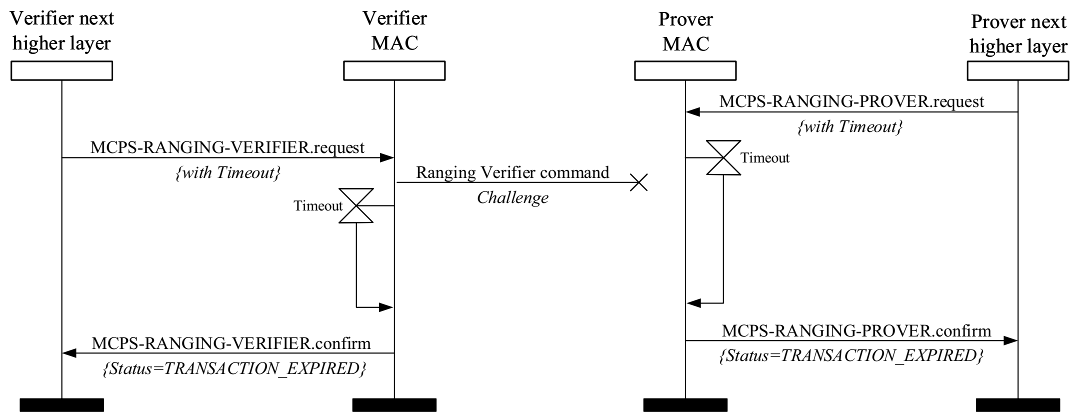

Figure 6-48z6—Message sequence chart for basic ACRR with challenge timeout

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 6-48z7.

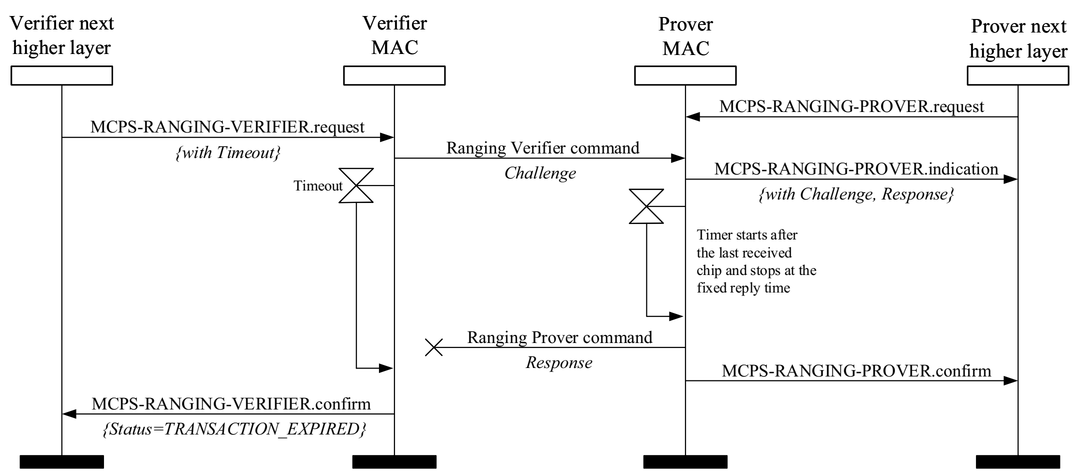

Figure 6-48z7—Message sequence chart for basic ACRR with response timeout

6.9.8.2 Security levels

6.9.8.2.1 General

ACRR supports various security levels defining the length of the cryptographic challenge and response data as per Table 6-4g. Validating the authenticity of the response relies on the services provided by Clause 9.

Table 6-4g—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

6.9.8.2.2 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 6-4h 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 6-4h—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” [B20a].

6.9.8.3 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 7.4.4.53 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' AcrrcIeIncluded 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.

6.9.8.4 ACRR Procedures

6.9.8.4.1 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.

6.9.8.4.2 ACRR based SS-TWR with one-way authentication

Figure 6-48z8 shows the message sequence for SS-TWR with one-way authentication.

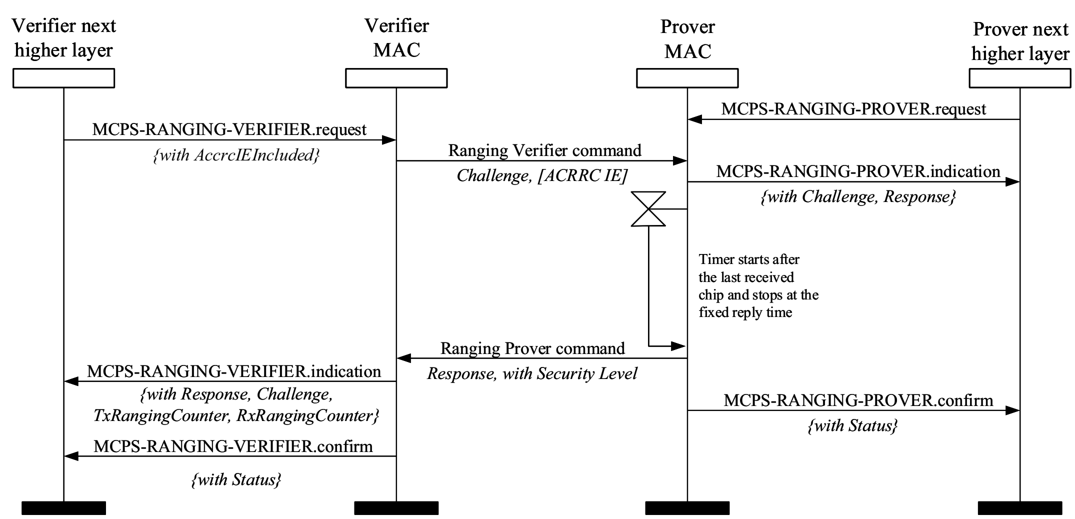

Figure 6-48z8—Message sequence chart for SS-TWR with one-way authentication

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 6-4i defines the content of the MAC commands.

Table 6-4i—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

6.9.8.4.3 ACRR based SS-TWR with one-way authentication and tolerance of bit errors in the challenges

Figure 6-48z9 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.

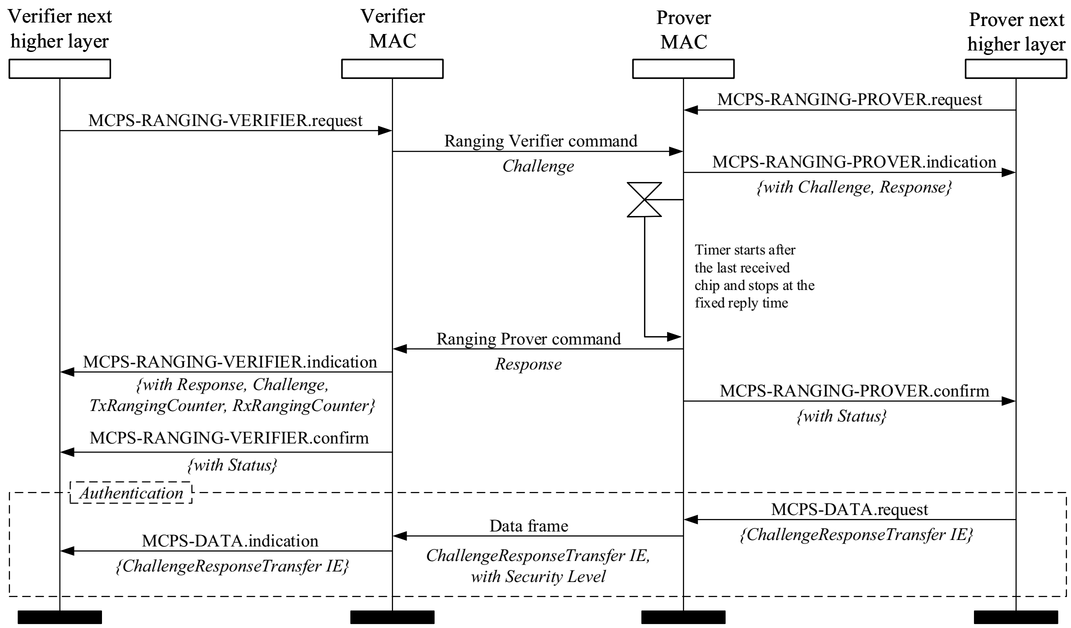

Figure 6-48z9—Message sequence chart SS-TWR with one-way authentication and tolerance of bit errors

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 is sufficient to ensure 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 6-4j defines the content of the MAC commands.

Table 6-4j—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

6.9.8.4.4 ACRR based DS-TWR with one-way authentication

Figure 6-48z10 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 *phyFixedReplyTimeSupported* equal to FALSE or have longer post-processing time during frame reception.

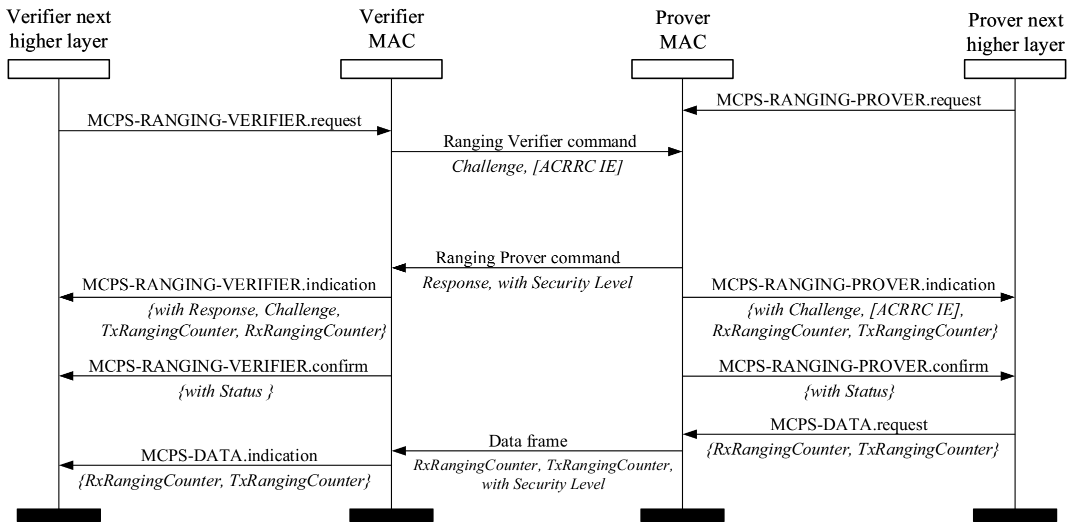

Figure 6-48z10—Message sequence chart for DS-TWR with one-way authentication

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 ACRRC 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 ACRRC 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 PChallenge 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 that a security level of one, two or three is sufficient to protect the integrity.

Table 6-4k defines the content of the MAC commands.

Table 6-4k—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

6.9.8.4.5 ACRR based SS-TWR with mutual authentication

Figure 6-48z11 describes the message exchange for SS-TWR with mutual authentication and fixed reply time.

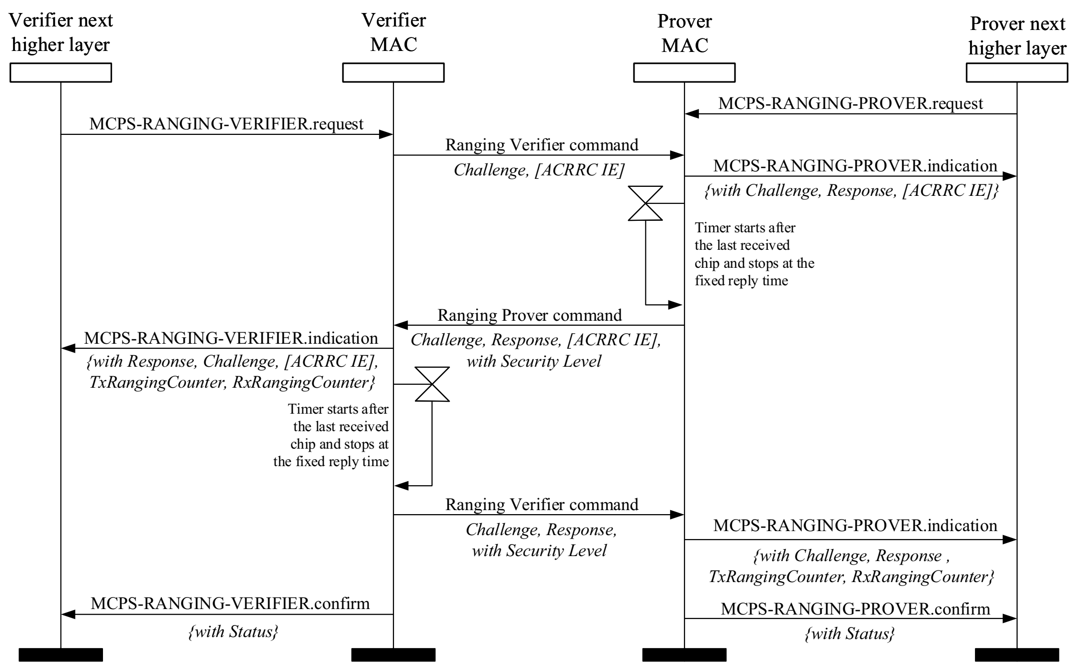

Figure 6-48z11—Message sequence chart for SS-TWR with mutual authentication

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 6-4l defines the content of the MAC commands.

Table 6-4l—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	

6.9.8.4.6 ACRR based SS-TWR with mutual authentication and tolerance of bit errors in the challenges

Figure 6-48z12 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).

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 VChallenge_1 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 VChallenge_1, 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.

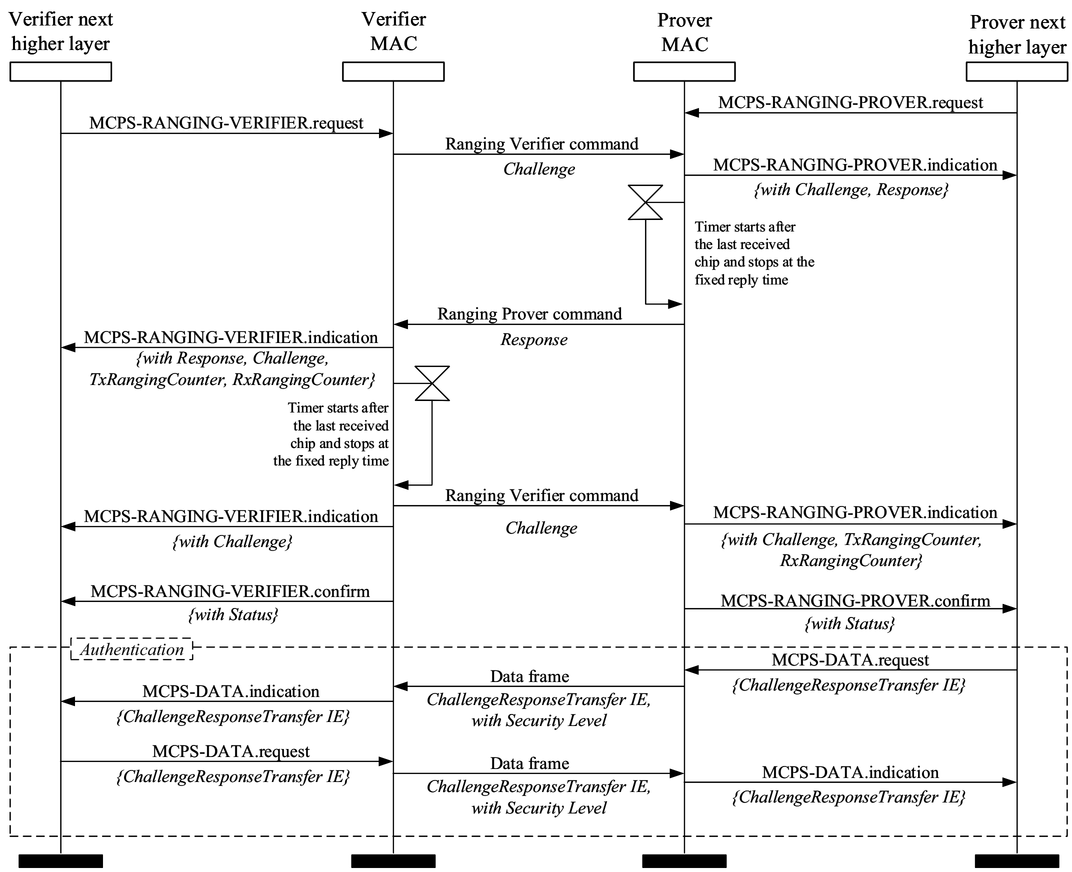

Figure 6-48z12—Message sequence chart for SS-TWR with mutual authentication and tolerance of bit errors

The verifier MAC receives the PChallenge, starts the timer of the fixed reply time procedure, indicates the received $\mathrm{VChallenge}_1$ to the next higher layer, and generates a fresh $\mathrm{VChallenge}_2$ 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 $\mathrm{VChallenge}_2$ in its Challenge field and confirms the status to the next higher layer. The prover MAC receives the Ranging Verifier command, indicates the received $\mathrm{VChallenge}_2$ 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 $\mathrm{VChallenge}_1$ 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 $\mathrm{VChallenge}_2$ 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 6-4m defines the content of the MAC commands.

Table 6-4m—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	

6.9.8.4.7 ACRR based DS-TWR with mutual authentication

DS-TWR with mutual authentication makes use of two 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 *phyFixedReplyTimeSupported* equals FALSE) or that require longer post-processing time during frame reception and therefore need to exchange ranging counter information.

Figure 6-48z13 describes the message exchange for DS-TWR with mutual authentication without a fixed reply time.

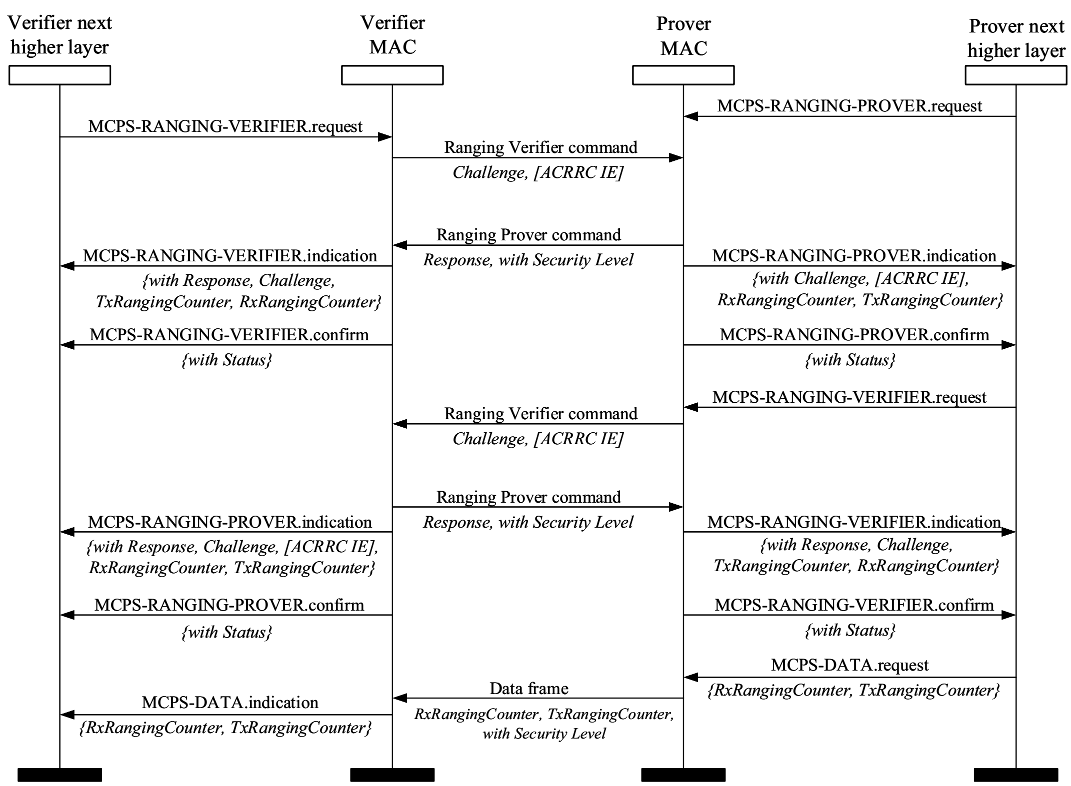

Figure 6-48z13—Message sequence chart for DS-TWR with mutual authentication

The verifier performs an SS-TWR with one-way authentication with the prover as described in 6.9.8.1 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.

The DS-TWR with mutual authentication completes with a data frame initiated by the prover containing the ranging counters with security level. Note that security levels of 1 to 3 are sufficient to verify the integrity of the ranging counter values.

Table 6-4n summarizes content of the Ranging Verifier commands and Ranging Prover commands exchanged during DS-TWR with mutual authentication.

Table 6-4n—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	$VChallenge_1$	
2		$VChallenge_1$
3	$VChallenge_2$	
4		$VChallenge_2$

6.9.8.4.8 ACRR based SS-TWR with one-way authentication for multiple nodes

Figure 6-48z14 shows the message exchange for SS-TWR with one-way authentication with one verifier and multiple prover devices.

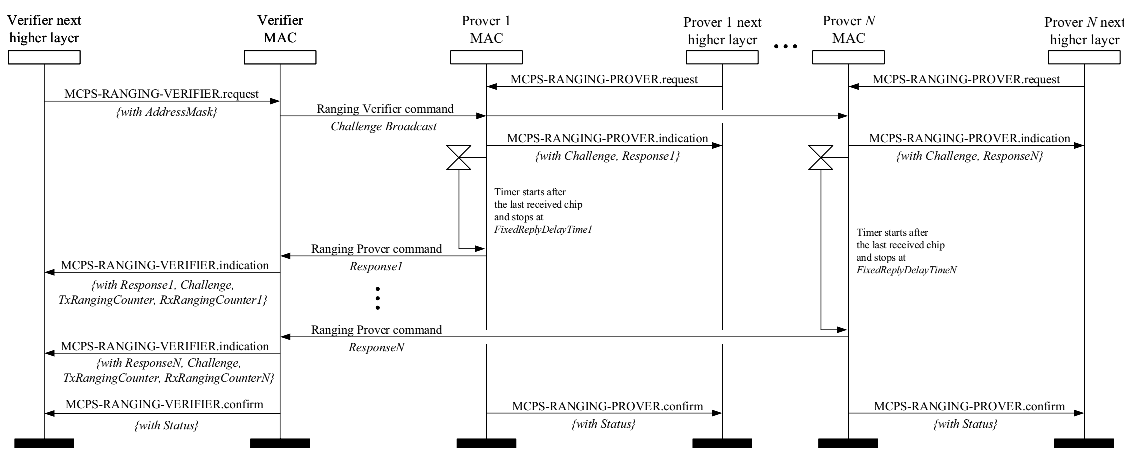

Figure 6-48z14—Message sequence chart for ACRR based multi-node SS-TWR with one-way authentication

The next higher layer in each prover device should pre-configure the device's fixed reply time referred to in Figure 6-48z14 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…*N*) and each Response (1…*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.

6.9.9 Ranging message non-receipt exchange

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 6-48z15, 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 7.4.4.50, 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.

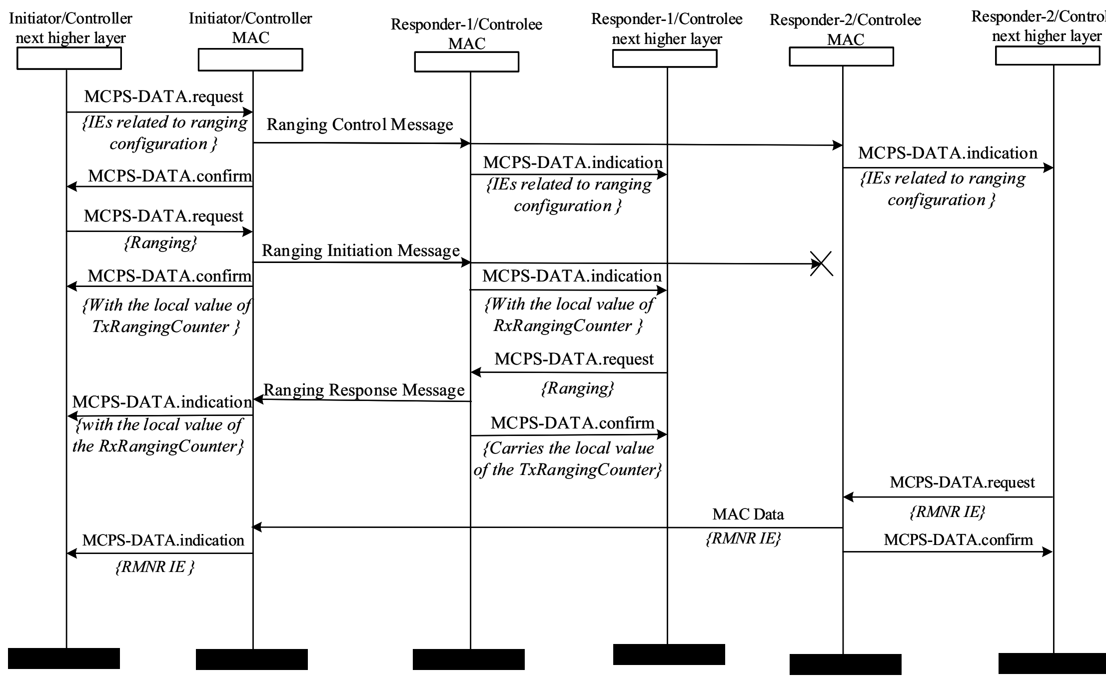

Figure 6-48z15—Ranging message non-receipt exchange for one initiator and multiple responders: controller is a ranging initiator

6.9.10 Ranging ancillary information

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 schedule-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 7.4.4.36). The next higher layer can use the fields of the Ranging Ancillary Information Message Counter and Type IE (RAICT IE), as described in 7.4.4.51, 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.

6.9.11 Multiple Message Receipt Confirmation

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 7.4.4.52, 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 6-48z16 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_{Aj} is the ith 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.

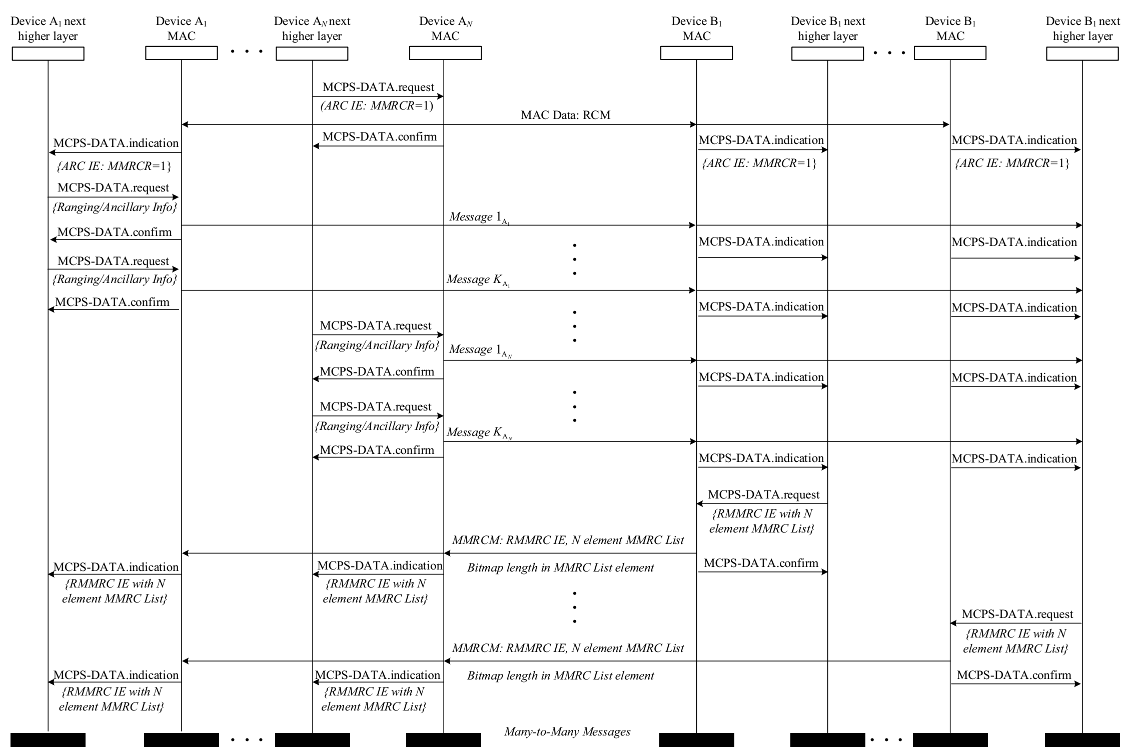

Figure 6-48z16—Message sequence chart showing example use of MMRCM

7. MAC frame formats

7.2 General MAC frame format

7.2.11 FCS field

Add a new paragraph after the first paragraph of 7.2.11 as follows:

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

7.4 IEs

7.4.2 Header IEs

7.4.2.1 Header IE format

Change the row for Element ID "0x2c–0x7d" in Table 7-7 and insert a new row above it as follows (unchanged rows not shown):

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
…										
0x2c	Ranging STS Key and Data IE (RSKD IE)			X			7.4.2.20	6.9.6.8	UL	UL
~~0x2c~~0x2d–0x7d	Reserved									

Insert new subclause 7.4.2.20 after 7.4.2.19 as follows:

7.4.2.20 Ranging STS Key and Data IE (RSKD IE)

The RSKD IE header IE content is formatted exactly the same as the RSKD IE payload IE specified in 7.4.4.42. This header IE facilitates synchronization of STS generators using information sent in the clear, while accompanied by secured payload IEs and data.

7.4.4 Nested IE

7.4.4.1 Format of Nested IE

Change the rows for Sub-ID values of 0x39 and above in Table 7-18 as follows (other unchanged rows not shown):

Table 7-18—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
…										
0x39	Multi-PHY IE	X	X	X	X		7.4.4.34	17.3	UL	UL
0x3a–0x3f	Reserved									
0x40	Vendor Specific IE	X	X	X	X	X	7.4.4.30	—	UL	UL
~~0x3a–0x3f~~ 0x41–0x45 ~~0x47–0x7f~~	Reserved									
0x46	SRM IE	X			X	X	7.4.2.17	6.16.3.2	UL	UL, MAC
0x47	Reserved									
0x48	Ranging Reply Time Instantaneous IE (RRTI IE)			X			7.4.4.35	6.9.6.4, 6.9.6.7, 6.9.7.4, 6.9.7.5, 6.9.7.6, 6.9.7.7	UL	MAC
0x49	Advanced Ranging Control IE (ARC IE)			X			7.4.4.36	6.9.7	UL	UL
0x4a	Ranging Interval Update IE (RIU IE)			X			7.4.4.37	6.9.7.3.2	UL	UL
0x4b	Ranging Round IE (RR IE)			X			7.4.4.38	6.9.7.3.3	UL	UL
0x4c	Ranging Block Update IE (RBU IE)			X			7.4.4.39	6.9.7.3.3	UL	UL
0x4d	Ranging Contention Phase Structure IE (RCPS IE)			X			7.4.4.40	6.9.7.2	UL	UL
0x4e	Ranging Contention Maximum Attempts IE (RCMA IE)			X			7.4.4.41	6.9.7	UL	UL
0x4f	Ranging STS Key and Data IE (RSKD IE)			X			7.4.4.42	6.9.6.8	UL	UL
0x50	Ranging Change Request IE (RCR IE)			X			7.4.4.43	6.9.7.3.2	UL	UL

Table 7-18—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
0x51	Ranging Device Management IE (RDM IE)			X			7.4.4.44	6.9.7	UL	UL
0x52	Ranging Request Measurement and Control IE (RRMC IE)			X			7.4.4.45	6.9.6.3, 6.9.6.4, 6.9.6.6, 6.9.6.7, 6.9.7.4, 6.9.7.5, 6.9.7.6, 6.9.7.7	UL	UL
0x53	Ranging Measurement Information IE (RMI IE)			X			7.4.4.46	6.9.6.3, 6.9.6.4, 6.9.6.6, 6.9.6.7, 6.9.7.4, 6.9.7.5, 6.9.7.6, 6.9.7.7	UL	UL, MAC
0x54	SP3 Ranging Request Reports IE (SRRR IE)			X			7.4.4.47	6.9.7.8.2, 6.9.7.8.3	UL	UL
0x55	Ranging Channel and Preamble Code Selection IE (RCPCS IE)			X			7.4.4.48	6.9.6.8	UL	UL
0x56	Ranging Reply Time Negotiation IE (RRTN IE)			X			7.4.4.49	6.9.6.4, 6.9.6.5	UL	UL
0x57	Ranging Message Non Receipt IE (RMNR IE)			X			7.4.4.50	6.9.9	UL	UL
0x58	Ranging Ancillary Information Message Counter and Type IE (RAICT IE)			X			7.4.4.51	6.9.10	UL	UL
0x59	Ranging Multiple Message Receipt Confirmation IE (RMMRC IE)			X			7.4.4.52	6.9.11	UL	UL
0x5a	Authenticated Challenge-Response Ranging Control IE (ACRRC IE)					X	7.4.4.53	6.9.8.3, 6.9.8.4	UL, MAC	UL, MAC
0x5b	Ranging Descriptor IE (RD IE)	X					7.4.4.54	6.2.11	UL	UL
0x5c	ChallengeResponseTransfer IE			X			7.4.4.55	6.9.8.4.2, 6.9.8.4.5	UL	UL
0x5d–0x7f	Reserved									

Insert new subclauses 7.4.4.35 to 7.4.4.55 after 7.4.4.34 as follows:

7.4.4.35 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 7.4.4.45) 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 7-106a.

Bits: 0–1	2–7	Octets: variable
Address Size Specifier	RRTI List Length	RRTI List

Figure 7-106a—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 7-52a.

Table 7-52a—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 7-106b.

Octets: 4	0/2/8
RX-to-TX Reply Time	Address

Figure 7-106b—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 6.9.1.4. The general procedures for using the RRTI IE are specified in 6.9.6.

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.

7.4.4.36 Advanced Ranging Control IE (ARC IE)

The ARC IE is used by a controller to send the ranging configuration information to a controlee (in a unicast frame) or multiple controlees (in a broadcast frame) as described in 6.9.7. The ARC IE can also be used by the controlee, along with the RCR IE (described in 7.4.4.43), to send preferred ranging parameters to the controller. The Content field of the ARC IE shall be formatted as shown in Figure 7-106c.

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 7-106c—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 values specified in Table 7-52b.

Table 7-52b—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 7-52c.

Table 7-52c—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 6.9.1.2.5
1	Single-sided two-way ranging (SS-TWR), see 6.9.1.2.2.
2	Doube-sided two-way ranging (DS-TWR), see 6.9.1.2.3.
3	Ranging ancillary information exchange, see 6.9.10.

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 7-52d. For devices that are not HRP-ERDEV this field shall be set to zero.

Table 7-52d—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 per specified in Table 15-a.
2	STS packet structure #2 as per specified in Table 15-a.
3	STS packet structure #3 as per specified in Table 15-a.

The Schedule Mode field specifies whether the scheduling-based ranging or contention-based ranging is performed as per Table 7-52e.

Table 7-52e—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 7.4.4.44 and the RCPS IE as described in 7.4.4.40 are employed to control participation.
1	Scheduled-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 exchange of deferred data frame(s) after the ranging cycle, 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 RFRAME, for example RRTI IE as described in 7.4.4.35.

The Time Structure Indicator field specifies the ranging time structure behavior in the following ranging rounds as per Table 7-52f.

Table 7-52f—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 7.4.4.37 is used to control the ranging interval updates.
1	The time structure is block-based and the RR IE described in 7.4.4.38 and RBU IE described in 7.4.4.39 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 6.9.11,

The Content Control field is formatted as per Figure 7-106d, indicating presence or not of other fields in the ARC IE.

Bits: 0	1	2	3	4–7
RBDP	RRDP	RSDP	SIP	Reserved

Figure 7-106d—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 6.9.1.5).

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 key 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 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.

7.4.4.37 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 7-106e.

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 7-106e—RIU IE Content field format

The Content Control field is formatted as per Figure 7-106f, 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 7-106f—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 7-52g.

The Block Interval field indicates the time remaining in RTSU (as defined in 6.9.1.5) 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.

Table 7-52g—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 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 7-52h.

Table 7-52h—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 6.9.7.3.2.

7.4.4.38 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 6.9.7.3.3. The Content field of the RR IE shall be formatted as shown in Figure 7-106g.

Octets: 2	Bits: 0	1–15	Octets: 2
Ranging Block Index	Hopping Mode	Round Index	Transmission Offset

Figure 7-106g—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.

7.4.4.39 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 controllee, 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 7-106h.

Octets: 1	3	1/0	2/0
Relative Ranging Block Index	Updated Block Duration	Updated Ranging Round Duration	Updated Slot Duration

Figure 7-106h—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 6.9.1.5). 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 that 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.

7.4.4.40 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 7-106i.

Octets: 1	variable
CP Table Length	CP Table

Figure 7-106i—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 7-106j, 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 7-106j—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 7-52i.

Table 7-52i—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.

The RCPS IE is used in the multi-node ranging procedures described in 6.9.7, which includes description of the ranging phases and the slot indexing scheme.

7.4.4.41 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 7-106k.

Octets: 1
Max Contention Attempts

Figure 7-106k—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 7.4.4.36).

7.4.4.42 Ranging STS Key and Data IE (RSKD IE)

The RSKD IE can be used to convey and align the seed, (i.e., STS key and data), used for STS generation. The Content field of the RSKD IE shall be formatted as shown in Figure 7-106l.

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	SKP	ACP	CP	V3	V2	V1	V Counter	STS Key	Application Code

Figure 7-106l—RSKD 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 SKP field value of one indicates the presence of the STS Key field, and the value zero means it is not present.

The ACP field indicates the presence of the Application Code field as per Table 7-52j.

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 RSKD 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.

Table 7-52j—Values of the ACP field in the RSKD IE

ACP field value	Meaning
0	The Application Code field is not present in the RSKD IE
1	A 4-octet Application Code field is present in the RSKD IE
2	An 8-octet Application Code field is present in the RSKD IE
3	A 16-octet Application Code field is present in the RSKD IE

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 Key field, if present, contains a 16-octet string to initialize the STS key.

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 7-52j.

The fields of the RSKD IE are determined and consumed by the next higher layer. The next higher layer is responsible for validating these as necessary and programming the *phyHrpUwbStsKey*, *phyHrpUwbStsVUpper96*, and *phyHrpUwbStsVCounter* PIB attributes accordingly.

The STS Key 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 15-7b, the octet received first in time is the treated as the most significant octet.

In the case that the contents of the RSKD IE are confidential, its security level shall be 5 or higher.

7.4.4.43 Ranging Change Request IE (RCR IE)

The RCR IE is sent by a controlee 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 7.4.4.36) and/or an RIU IE (described in 7.4.4.37). In block-based mode the RCR IE shall be accompanied by an RR IE (described 7.4.4.38) and/or an RBU IE (described in 7.4.4.39). Other IEs may also be included for other reasons. Since the preferred parameters and intervals from controlee(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.

7.4.4.44 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 7-106m.

Bits: 0	1	2–7	Octets: variable
SIU	Address Size	RDM List Length	RDM List

Figure 7-106m—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 controlees 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 controlees 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 7-106n. 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 7-106n—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 unused/reserved.

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 controlee knows whether it is selected to participate in the ranging round(s).

7.4.4.45 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 7-106o.

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 7-106o—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 7-52k, to indicate the function of the frame as described in the procedures defined in 6.9.6 and 6.9.7.

Table 7-52k—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 6-48v, 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 6-48z, the initiator can request the resultant TOF 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.

7.4.4.46 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 7-106p.

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 7-106p—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 7-52a.

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 7-106q.

Octets: 0/4	**0/4**	**0/4**	**0/2**	**0/1**	**0/2**	**0/1**	**0/2/8**
TX-to-RX Reply Time	TX-to-RX Round-trip Time	TOF	AOA Azimuth	AOA Azimuth FOM	AOA Elevation	AOA Elevation FOM	Address

Figure 7-106q—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 6.9.1.4.

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 6.9.1.4.

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 6.9.6 and 6.9.7.

7.4.4.47 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 requestor to a provider. The Content field of the SRRR IE shall be formatted as shown in Figure 7-106r.

Bits: 0–1	**2–3**	**4**	**5**	**6**	**7**	**Octets: 0/2/8**	**0//2/8**
Requestor Address Size Specifier	Provider Address Size Specifier	RAOA	RRT	RRTT	RTOF	Requestor Address	Provider Address

Figure 7-106r—SRRR IE Content field format

The Requestor Address Size Specifier field specifies the size of the Requestor Address field, as per the definition in Table 7-52a.

The Provider Address Size Specifier field specifies the size of the Provider Address field, as per the definition in Table 7-52a.

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 Requestor 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 controlees (responders), the SRRR IE in the RCM does not need to incorporate the address field of the requestor, since responders implicitly know that requests are from the controller (initiator).

In unicast SP3 ranging, the SRRR IE can be sent without requestor address or provider address fields. In this case the MHR source address identifies the requestor and the provider is the receiving device.

7.4.4.48 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 6.9.4.1, for a forthcoming ranging exchange. The Content field of the RCPCS IE shall be formatted as shown in Figure 7-106s.

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 7-106s—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 10.1.3.5 for the HRP UWB PHY and 10.1.3.8 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 6.9.1.5) 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 15-7, or both from Table 15-7a.

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 15.2.6.2, 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.

7.4.4.49 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 7.4.4.35) 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 7-106t.

Bits: 0–3	4–7	Octets: 0/4	0/2
Type	Reserved	Reply Time	Precision

Figure 7-106t—RRTN IE Content field format

The Type field specifies the function of the IE with respect to the reply time, as per Table 7-52l.

Table 7-52l—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 7.4.4.35) 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 7-52l. 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 6.9.1.4. 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 6.9.6.4.

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 6.9.6.5. Fixed reply times can also be used when performing DS-TWR.

7.4.4.50 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 6.9.7.

7.4.4.51 Ranging Ancillary Information Message Counter and Type IE (RAICT IE)

The RAICT IE is used during ranging ancillary information exchange as described in 6.9.10, The Content field of the RAICT IE shall be formatted as shown in Figure 7-106u.

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 7-106u—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.

7.4.4.52 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 7-106v.

Bits: 0	**1**	**2–7**	**Octets: 1**	**variable**
Address Present	Address Size	Reserved	MMRC List Length	MMRC List

Figure 7-106v—RMMRC IE Content field format

The Address Present field when one indicates that 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, 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 7-106w.

Octets: 0/2/8	**1**	**variable**
Address	MMRC Bitmap Length	MMRC Bitmap

Figure 7-106w—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 ExtraBits = (NumberOfBitsinMMRCBitmap – NumberOfSlotsForReceiptConfirmation) are discarded.

7.4.4.53 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 7-106x.

Bits: 0–1	**2–4**	**5–7**
Authenticated Ranging Method	Security Level	Reserved

Figure 7-106x—ACRRC IE Content field format

The Authenticated Ranging Method field defines the ranging method and type of authentication used as specified in Table 7-52m.

Table 7-52m—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.

7.4.4.54 Ranging Descriptor IE (RD IE)

The RD IE is employed in Enhanced Beacon frames to specify the time structure for ranging, as described in 6.2.11. The Content field of the RD IE shall be formatted as shown in Figure 7-106y.

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 7-106y—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 RSTUs (as defined in 6.9.1.5).

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 7-106z 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 7-106z—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.

7.4.4.55 ChallengeResponseTransfer IE

The ChallengeResponseTransfer IE conveys challenge or response data between devices performing the ranging as described in 6.9.8.4.2 and 6.9.8.4.5. The ChallengeResponseTransfer IE Content field shall be formatted as shown in Figure 7-106z.

Bits: 0	1–7	Octets: 4 to 64
Type	Length	Data

Figure 7-106z1—RD 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.

7.5 MAC commands

7.5.1 Command ID field

***Change the row for Command ID "0x29–0xff" in Table 7-53 and insert two new rows for "0x29" and "0x2a" above it as follows (unchanged rows not shown):*.**

Table 7-53—MAC commands

Command ID	Command name	RFD		Subclause
		TX	RX	
…				
0x29	Ranging Verifier command			7.5.31
0x2a	Ranging Prover command			7.5.32
~~0x29~~0x2b–0xff	Reserved			

Insert new subclauses 7.5.31 and 7.5.32 after 7.5.30 as follows:

7.5.31 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 7-147.

Octets: 1	4/8/16/32/64
Reserved	Challenge

Figure 7-147—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 parameter of the MCPS-RANGING-VERIFIER.request primitive, as per Table 6-4g.

In the case of the ACRR modes with tolerance of bit errors as described in 6.9.8.4.3 and 6.9.8.4.6, 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 6-4h.

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).

7.5.32 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 7-148.

Octets: 1	**4/8/16/32/64**
Reserved	Response

Figure 7-148—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 6.9.8.4.

In the case of ranging modes with tolerance of bit errors as described in 6.9.8.4.3 and 6.9.8.4.6, 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 6-4h. The generation of the response data should use a cryptographically secure pseudo-random number generator (CSPRNG).

8. MAC services

8.2 MAC management service

8.2.1 Primitives supported by the MLME-SAP interface

Insert a new row into Table 8-1 as follows:

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

Name	Request	Indication	Response	Confirm
MLME-STS	8.2.27.1			8.2.27.2

8.2.5 Communications notification primitives

8.2.5.2 MLME-BEACON-NOTIFY.indication

Change the row for "Timestamp" in Table 8-12 as follows (unchanged rows not shown):

Table 8-12—Elements of PANDescriptor

Name	Type	Valid range	Description
…			
TimeStamp	Integer	0x000000–0xffffff	For non-ERDEV, the ~~The~~ time at which the Beacon frame was received, in symbol periods. This value is equal to the timestamp taken when the Beacon frame was received, as described in 6.5.2. This value shall be accurate to 16 symbol periods. For ERDEV, this shall be the time in RSTU (as defined in 6.9.1.5) corresponding to the start of the received packet (preamble) for the Beacon frame.
…			

8.2.10 Primitives for specifying the receiver enable time

8.2.10.2 MLME-RX-ENABLE.request

Change 8.2.10.2 as follows:

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,
                              RxOnTime,
                              RxOnDuration,
                              RxAutoOff,
                              RangingControl
                              RangingRxControl
                              )
```

The primitive parameters are defined in Table 8-27.

Table 8-27—MLME-RX-ENABLE.request parameters

Name	Type	Valid range	Description
DeferPermit	Boolean	TRUE, FALSE	TRUE if the requested operation can be deferred until the next superframe if the requested time has already passed. FALSE if the requested operation is only to be attempted in the current superframe. For non-ERDEVs, this ~~This~~ parameter is ignored for nonbeacon-enabled PANs. For an ERDEV in a nonbeacon-enabled PAN, TRUE indicates that the requested operation can be deferred for more than half a period of the RSTU counter, and FALSE indicates that the requested operation is only to be attempted within the current half period of the RSTU counter. If the issuing device is the PAN coordinator, the term *superframe* refers to its own superframe. Otherwise, the term refers to the superframe of the coordinator through which the issuing device is associated.
RxOnTime	List of integers ~~Integer~~	0x000000–0xffffff	For non-ERDEV this parameter is a single integer that specifies the ~~The~~ number of symbols measured from the start of the superframe before the receiver is to be enabled or disabled. This is a 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. This parameter is ignored for nonbeacon-enabled PANs. If the issuing device is the PAN coordinator, the term *superframe* refers to its own superframe. Otherwise, the term refers to the superframe of the coordinator through which the issuing device is associated. For ERDEV, this parameter is a list of receiver enable time(s) in RSTU, as defined in 6.9.1.5.
RxOnDuration	List of integers ~~Integer~~	0x000000–0xffffff	For non-ERDEV, this parameter is a single integer that specifies the ~~The~~ number of symbols for which the receiver is to be enabled. If this parameter is equal to 0x000000, the receiver is to be disabled. If this parameter is equal to 0xffffff, the receiver is to be enabled indefinitely.

Table 8-27—MLME-RX-ENABLE.request parameters *(continued)*

Name	Type	Valid range	Description
RxAutoOff	List of Booleans	TRUE, FALSE	This parameter is a list with one element for each RxOnDuration list element. 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. Where there is additional RxOnTime/RxOnDuration list element(s), the receiver will be re-enabled at the specified time(s) accordingly.
RangingControl ~~RangingRxControl~~	Enumeration	RANGING_OFF, RANGING_ON	A value of RANGING_OFF disables ranging and a value of RANGING_ON enables ranging. ~~Configure the transceiver to Rx with ranging for a value of RANGING_ON or to not enable ranging for RANGING_OFF.~~

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 beacon-enabled PAN or immediately on a nonbeacon-enabled PAN, or at a specified time in RSTU for an ERDEV. This primitive is also generated to cancel a previously generated request to enable the receiver. The receiver is enabled or disabled exactly once per primitive request, except for ERDEV where the RxOnTime and RxOnDuration may supply a list of enable times and durations.

For ERDEVs the next higher layer can use the TimeStamp parameters of MCPS-DATA.indication, MCPS-DATA.confirm, and MLME-BEACON-NOTIFY.indication as the reference to specify the RxOnTime(s).

The MLME will treat ~~the~~ 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, ~~or~~ 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, ~~or~~ 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.

For ERDEVs, when the RxOnTime, RxOnDuration, and RxAutoOff parameters are lists, the receiver will be re-enabled at the specified time(s) for the specified durations(s) as modified by the RxAutoOff value(s) until the list is exhausted, or until a new MLME-RX-ENABLE.request is issued with an RxOnDuration parameter of zero, which shall disable the receiver and cancel any outstanding receiver enable(s) in the list. When provided as a list, the RxOnTimes shall be in the chronological order of the required receiver enable times. When the RxOnTime is an empty list, the Receiver is turned on immediately for the specified RxOnDuration. When the RxOnTime, RxOnDuration and RxAutoOff parameters are multiple entry lists, the lists shall all contain the same number of elements, otherwise MLME shall issue the MLME-RXENABLE.confirm primitive with a Status of INVALID_PARAMETER. Typically, the next higher layer will not invoke a new MLME-RX-ENABLE.request primitive until the current list has been completed. However, a new MLME-RX-ENABLE.request shall disable the receiver if it is enabled at the time the new primitive is issued, cancel outstanding receiver enables from any previous MLME-RX-ENABLE.request primitives, and thereafter perform the receiver enables and disables specified by the new primitive.

For non-ERDEVs on ~~On~~ a nonbeacon-enabled PAN, the MLME ignores the DeferPermit and RxOnTime parameters and requests that the PHY enable or disable the receiver immediately. If the request is to enable the receiver, the receiver will remain enabled until RxOnDuration has elapsed.

For ERDEVs on a non-beacon-enabled PAN, when an MLME-RX-ENABLE.request primitive is issued specifying an initial RxOnTime with an RSTU 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 RSTU counter reaches the specified RxOnTime value to enable the receiver.

Before attempting to enable the receiver on a beacon-enabled PAN, the MLME first determines whether (RxOnTime + RxOnDuration) is less than the beacon interval, as defined by *macBeaconOrder*. If (RxOnTime + 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.

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 (RxOnTime – *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 (RxOnTime – *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.

If the RxOnDuration parameter is equal to zero, the MLME requests that the PHY disable its receiver.

8.2.10.3 MLME-RX-ENABLE.confirm

Change 8.2.10.3 as follows:

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 8-28.

Table 8-28—MLME-RX-ENABLE.confirm ~~parameter~~ parameters

Name	Type	Valid range	Description
StatusDetail	List of Enumeration	SUCCESS, PAST_TIME, ON_TIME_TOO_LONG	This is an optional parameter providing a list of result values corresponding with the list of RxOnTime, RxOnDuration, and RxAutoOff parameters passed into the MLME-RX-ENABLE.request primitive.
Status	Enumerations ~~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 optional parameter StatusDetail is a list that may be provided in the case of a failure, to give additional information, with a status detail value for each listed entry of the RxOnTime, RxOnDuration (and RxAutoOff) parameters passed into the MLME-RX-ENABLE.request primitive.

A Status value of INVALID_PARAMETER is returned if RxOnTime, RxOnDuration, and RxAutoOff, parameters passed to the MLME-RX-ENABLE.request primitive are multiple entry lists of different length.

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 8.2.10.2.

Insert new subclause 8.2.10.4 after 8.2.10.3 as follows:

8.2.10.4 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 8-28a.

Table 8-28a—MLME-RX-ENABLE.indication parameters

Name	Type	Valid range	Description
TimeStamp	Integer	0x000000–0xffffff	Reports the time at which the receiver disable occurred. For an ERDEV, the time is reported in RSTU. For a non-ERDEV, the time is reported in symbols.

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 RxOnTime, RxOnDuration (and RxAutoOff) parameters are lists, 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 that the reception of a data frame during the enable period is indicated by the MAC using the MCPS-DATA.indication primitive.

Change the title of 8.2.15 as follows:

8.2.15 Primitives for specifying dynamic channel and preamble selection

Change 8.2.15.2, 8.2.15.3, and 8.2.15.4 as follows:

8.2.15.2 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~~ for a single use pending expiration of the DpsIndexDuration~~ and/or channel number temporarily overriding the *phyCurrentCode* and/or *phyCurrentChannel* attribute settings.

The semantics of this primitive are as follows:

```
MLME-DPS.request        (
                        ~~TxDpsIndex~~TxDpsIndex,
                        ~~RxDpsIndex~~RxDpsIndex,
                        ChannelNumber,
                        DpsDuration,
                        ConfigTime
                        ~~DpsIndexDuration~~
                        )
```

The primitive parameters are defined in Table 8-37.

Table 8-37—MLME-DPS.request parameters

Name	Type	Valid range	Description
TxDpsIndex	Integer	0, 13–16, 21–32 ~~24~~	The index value for the transmitter. A value of zero ~~0~~ disables the index and indicates that the *phyCurrentCode* value is to be used, as defined in 15.2.6.2. Other values indicate the preamble code, as defined in Table 15-7 and Table 15-7a.
RxDpsIndex	Integer	0, 13–16, 21–32 ~~24~~	The index value for the receiver. A value of zero ~~0~~ disables the index and indicates that the *phyCurrentCode* value is to be used, as defined in 15.2.6.2. Other values indicate the preamble code, as defined in Table 15-7 and Table 15-7a.
ChannelNumber	Integer	–1, 0–15	UWB channel as per 10.1.3.5 for the HRP UWB PHY and 10.1.3.8 for the LRP UWB PHY, for the forthcoming message exchanges. A value of minus one disables the channel selection and indicates that the phyCurrentChannel value is to be used.

Table 8-37—MLME-DPS.request parameters *(continued)*

Name	Type	Valid range	Description
DpsDuration	Integer	0x000000–0xffffff	When non-zero this specifics 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 6.9.1.5). 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	0x000000–0xffffff	Specifies a future time at which the MLME is to apply the specified DPS change with reference to the RSTU time counter (defined in 6.9.1.5). 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.
~~DpsIndexDuration~~	~~Integer~~	~~0x000000–0xffffff~~	~~The number of symbols for which the transmitter and receiver will utilize the respective DPS indices if a MCPS-DATA.request primitive is not issued.~~

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 ~~can~~ may also be generated to cancel a previously generated request to enable dynamic preamble code and channel selection. ~~the transmitter and receiver dynamic preambles. The use of the index for the transmitter and receiver is enabled or disabled exactly once per primitive request.~~

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.

~~The MLME starts the timer that assures that the device returns to a normal operating state with default preambles if a following MCPS-DATA.request primitive does not occur. After starting the timer, the MLME responds with a MLME-DPS.confirm primitive with the appropriate Status parameter.~~

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.

8.2.15.3 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 8-38.

Table 8-38—MLME-DPS.confirm parameter

Name	Type	Valid range	Description
Status	Enumeration	SUCCESS, ~~DPS_~~NOT_SUPPORTED	The result of the request to enable or disable dynamic ~~preambles~~ 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 ~~DPS_~~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.

8.2.15.4 MLME-DPS.indication

The MLME-DPS.indication primitive indicates the expiration of the DpsDuration timer if it is running ~~DpsIndexDuration and the resetting of the DPS values in the PHY~~. 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 ()

~~If a MCPS-DATA.request primitive is not received before the timer expires, the MLME issues the MLME-DPS.indication primitive to the next higher layer.~~

8.2.16 Primitives for channel sounding

8.2.16.1 General

Insert new text at the end of 8.2.16.1 as follows:

For information on the use of the MLME-SOUNDING primitives, see section 7.1.1.4.5 of “Applications of IEEE Std 802.15.4” [B3].

8.2.17 Primitives for ranging calibration

8.2.17.1 General

Insert new text at the end of 8.2.17.1 as follows:

For information on the use of the MLME-CALIBRATE primitives, see section 7.1.1.6 of “Applications of IEEE Std 802.15.4” [B3].

8.2.18 Primitives for Beacon Generation

Insert new subclause 8.2.18.4 after 8.2.18.3 as follows:

8.2.18.4 MLME-BEACON.indication

The semantics of this primitive are as follows:

```
MLME-BEACON.indication          (
                                Timestamp
                                )
```

The primitive parameters are defined in Table 8-44a.

Table 8-44a—MLME-BEACON.indication parameters

Name	Type	Valid range	Description
TimeStamp	Integer	0x000000–0xffffff	For non-ERDEV, this parameter reports the time, in symbols, at which the beacon was transmitted. The symbol boundary is described by *macSyncSymbolOffset*, as described in Table 8-81. The precision of this value shall be a minimum of 20 bits, with the lowest 4 bits being the least significant. For ERDEV, this shall be the time in RSTU (as defined in 6.9.1.5) corresponding to the start of the packet (preamble) for the transmitted beacon frame.

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.

8.2.25 RIT data commands

8.2.25.1 MLME-RIT-REQ.indication

Change the row for "Timestamp" in Table 8-71 as follows (unchanged rows not shown):

Table 8-71—MLME-RIT-REQ.indication parameters

Name	Type	Valid range	Description
…			
Timestamp	Integer	0x000000–0xffffff	<u>For non-ERDEV (</u>optional), the time, in symbol periods, at which the command was received, as described in 6.5.2. The symbol boundary is described by *macSyncSymbolOffset*, as described in Table 8-94. This value shall be accurate to 16 symbol periods. <u>For ERDEV (optional), the time in RSTU (as defined in 6.9.1.5) corresponding to the start of the packet (preamble) in which the command was received.</u>
…			

8.2.25.3 MLME-RIT-RES.indication

Change the row for "Timestamp" in Table 8-73 as follows (unchanged rows not shown):

Table 8-73—MLME-RIT-RES.indication parameters

Name	Type	Valid range	Description
…			
Timestamp	Integer	0x000000–0xffffff	For non-ERDEV (optional), the time, in symbol periods, at which the command was received, as described in 6.5.2. The symbol boundary is described by *macSyncSymbolOffset*, as described in Table 8-94. This value shall be accurate to 16 symbol periods. For ERDEV (optional), the time in RSTU (as defined in 6.9.1.5) corresponding to the start of the packet (preamble) in which the command was received.
…			

Insert new subclause 8.2.27 after 8.2.26 as follows:

8.2.27 Primitives for specifying STS parameters

8.2.27.1 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 8-86a.

Table 8-86a—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 15-a.
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 15-9e.

Table 8-86a—MLME-STS.request parameters *(continued)*

Name	Type	Valid range	Description
TxStsNumberSegments	Integer	0–3	This specifies the number of STS segments to use in the transmitter. The values are defined in Table 15-9f. 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 15-a.
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 15-9e.
RxStsNumberSegments	Integer	0–3	This specifies the number of STS segments to use in the receiver. The values are defined in Table 15-9f. 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:

— *phyHrpUwbStsTxPacketConfig*, *phyHrpUwbStsTxSegLen*, and *phyHrpUwbStsTxSegNum*,
— *phyHrpUwbStsRxPacketConfig*, *phyHrpUwbStsRxSegLen*, and *phyHrpUwbStsRxSegNum*.

The result of the STS configuration attempt is reported by the MLME-STS.confirm primitive.

8.2.27.2 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 8-86b.

Table 8-86b—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.

8.3 MAC data service

8.3.1 General

Insert new rows at the end of Table 8-87 as follows (unchanged rows not shown):

Table 8-87—MCPS-SAP primitives

MCPS-SAP primitive	Request	Confirm	Indication
…			
MCPS-RANGING-VERIFIER	8.3.7.1	8.3.7.2	8.3.7.3
MCPS-RANGING-PROVER	8.3.8.1	8.3.8.2	8.3.8.3

Insert new text at the end of 8.3.1 as follows:

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 6.9. 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 15.2, 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, 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 8-90a) parameter provides the 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 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).

8.3.2 MCPS-DATA.request

Change the first paragraph and the primitive semantics of 8.3.2 as follows:

The MCPS-DATA.request primitive requests <u>transmission</u> ~~the transfer of data~~ to another device.

The semantics of this primitive are as follows:

```
MCPS-DATA.request          (
                           SrcAddrMode,
                           DstAddrMode,
                           DstPanId,
                           DstAddr,
                           Msdu,
                           MsduHandle,
                           HeaderIeList,
                           PayloadIeList,
                           HeaderIeIdList,
                           NestedIeSubIdList,
                           AckTx,
                           GtsTx,
                           IndirectTx,
                           SecurityLevel,
                           KeyIdMode,
                           KeySource,
                           KeyIndex,
                           UwbPrf,
                           DataRequestRangingDescriptor,
                           Ranging,
                           UwbPreambleSymbolRepetitions,
                           DataRate,
                           LocationEnhancingInformationPostamble,
                           LocationEnhancingInformationPostambleLength,
                           PanIdSuppressed,
                           SeqNumSuppressed,
                           SendMultipurposeSendMultipurpose,
                           FrakPolicy,
                           CriticalEventMessage
                           )
```

Insert a new row in Table 8-88 after the row for "UwbPrf" as follows (unchanged rows not shown):

Table 8-88—MCPS-DATA.request parameters

Name	Type	Valid range	Description
…			
DataRequestRangingDescriptor	Structure	As in Table 8-88a.	Provides ranging related parameters.
…			

Delete the rows for "Ranging", "LocationEnhancingInformationPostamble", and "LocationEnhancingInformationPostambleLength" from Table 8-88.

Insert new text and Table 8-88a at the end of 8.3.2 as follows:

The DataRequestRangingDescriptor structure groups the ranging related parameters for the MCPS-DATA.request primitive. The elements of the DataRequestRangingDescriptor are defined in Table 8-88a.

Table 8-88a—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.
TxTimeSpecifie	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 TxTimeSpecfied is NONE, the transmission time is not specified by the RangingTxTime.
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 6.9.1.4. When TxTimeSpecified is RSTU_TIME, this parameter specifies the time to start transmitting the packet in the units defined in 6.9.1.5. When TxTimeSpecified is equal to NONE, this parameter is not used to specify the transmit time.
RequestRrtiTxList	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.
LocationEnhancingInfor-mationPostamble	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 aLeipDelayTime. A value of LEIP_NONE is used for non-LRP UWB PHYs.
LocationEnhancingInfor-mationPostambleLength	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 RequestRrtiTxList 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 7.4.4.35) into the frame prior to sending it, using the address/ranging counter pairs from the RequestRrtiTxList 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 RequestRrtiTxList. Each RRTI List element's address field shall be the corresponding address from the RequestRrtiTxList. The RRTI IE's address field may be omitted in the case of unicast ranging (where the RequestRrtiTxList 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 6.9.1.4. If ranging is not enabled or this constraint cannot be met (i.e., 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 6.9.1.5. 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 8-90a) parameter of the MCPS-DATA.confirm and MCPS-DATA.indication primitives.

8.3.3 MCPS-DATA.confirm

Change the first paragraph and the primitive semantics of 8.3.3 as follows:

The MCPS-DATA.confirm primitive reports the results of invoking the MCPS-DATA.request primitive ~~a request to transfer data to another device~~.

The semantics of the MCPS-DATA.confirm primitive are as follows:

```
MCPS-DATA.confirm          (
                           MsduHandle,
                           Timestamp,
                           RangingReportDescriptor,
                           RangingReceived,
                           RangingCounterStart,
                           RangingCounterStop,
                           RangingTrackingInterval,
                           RangingOffset,
                           RangingFom,
                           NumBackoffs,
                           HeaderIeList,
                           PayloadIeList,
                           AckPayload,
                           FramePendingFramePending,
                           Rssi,
                           Status
                           )
```

Change Table 8-89 as follows:

Table 8-89—MCPS-DATA.confirm parameters

Name	Type	Valid range	Description
MsduHandle	Integer	0x00–0xff	The handle associated with the MSDU being confirmed.
Timestamp	Integer	0x000000–0xffffff	For non-ERDEV (optional), the time, in symbol periods, at which the data were transmitted, as described in 6.5.2. ~~The value of this parameter will be considered valid only if the value of the Status parameter is SUCCESS; if the Status parameter is not equal to SUCCESS, the value of the Timestamp parameter shall not be used for any other purpose.~~ The symbol boundary is described by *macSyncSymbolOffset*, as described in Table 8-94. This value shall be accurate to 16 symbol periods. For ERDEV, this shall be the time in RSTU (as defined in 6.9.1.5) corresponding to the start of the transmitted packet (preamble). The value of this parameter will be considered valid only if the value of the Status parameter is SUCCESS; if the Status parameter is not equal to SUCCESS, the value of the Timestamp parameter shall not be used for any other purpose.
RangingReportDescriptor	Structure	As defined in Table 8-90a.	Reports ranging related results. This parameter is invalid if ranging is not supported or not enabled.
~~RangingReceived~~	~~Boolean~~	~~TRUE, FALSE~~	~~A value of FALSE indicates that ranging is either not supported by the PHY or that it was not indicated by the received PSDU. A value of TRUE indicates ranging operations were indicated for this PSDU.~~
~~RangingCounterStart~~	~~Unsigned Integer~~	~~0x00000000–0xffffffff~~	~~A count of the time units corresponding to an RMARKER at the antenna at the beginning of a ranging exchange, as described in 15.7.2. A value of 0x00000000 is used if ranging is not supported, not enabled or if counter was not used for this PPDU. A value of 0x00000000 is also used when one-way ranging is being employed. One-way ranging is described in “Applications of IEEE Std 802.15.4” [B3].~~
~~RangingCounterStop~~	~~Unsigned Integer~~	~~0x00000000–0xffffffff~~	~~A count of the time units corresponding to an RMARKER at the antenna at the end of a ranging exchange, as described in 15.7.2. A value of 0x00000000 is used if ranging is not supported, not enabled, or if the counter is not used for this PPDU. For one-way ranging this parameter reports the arrival time of the RMARKER at the antenna.~~

Table 8-89—MCPS-DATA.confirm parameters *(continued)*

Name	Type	Valid range	Description
~~RangingTrackingInterval~~	~~Integer~~	~~0x00000000–0xffffffff~~	~~A count of the time units in a message exchange over which the tracking offset was measured, as described in 15.7.3.3. If tracking-based crystal characterization is not supported or if ranging is not supported, a value of 0x00000000 is used.~~
~~RangingOffset~~	~~Signed Magnitude Integer~~	~~0x000000–0xffffff~~	~~A count of the time units slipped or advanced by the radio tracking system over the course of the entire tracking interval, as described in 15.7.3.2. The top 4 bits are reserved and set to zero. The most significant of the active bits is the sign bit.~~
~~RangingFoM~~	~~Integer~~	~~0x00–0x7f~~	~~The figure of merit (FoM) characterizing the ranging measurement, as described in 15.7.4.~~
NumBackoffs	Integer	0x00–0xff	The number of times the CSMA-CA algorithm was required to backoff as described in 6.2.3 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.
Rssi	Integer	0x00–0xff	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.

Table 8-89—MCPS-DATA.confirm parameters *(continued)*

Name	Type	Valid range	Description
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 ~~MSDU~~ transmission.

Insert new text at the end of 8.3.3 as follows:

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 “Applications of IEEE Std 802.15.4” [B3].

8.3.4 MCPS-DATA.indication

Change the first paragraph and the primitive semantics of 8.3.4 as follows:

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,
                            SecurityLevel,
                            KeyIdMode,
                            KeySource,
                            KeyIndex,
                            AckSent,
                            RangingReportDescriptor,
                            ~~RangingReceived,~~
```

~~RangingCounterStart,~~
~~RangingCounterStop,~~
~~RangingTrackingInterval,~~
~~RangingOffset,~~
~~RangingFom,~~
~~AngleOfArrivalAzimuth,~~
~~AngleOfArrivalElevation,~~
~~AngleOfArrivalSupported,~~
DataRate,
Rssi
)

Change Table 8-90 as follows (unchanged rows above the row for "Timestamp" not shown):

Table 8-90—MCPS-DATA.indication parameters

Name	Type	Valid range	Description
…			
Timestamp	Integer	0x000000–0xffffff	For non-ERDEV (optional), the time, in symbol periods, at which the data were received, as described in 6.5.2. The symbol boundary is described by *macSyncSymbolOffset*, as described in Table 8-94. This value shall be accurate to 16 symbol periods. For ERDEV, the time in RSTU (as defined in 6.9.1.5) corresponding to the start of the received packet (preamble).
SecurityLevel	Integer	0x00–0x07	The security level purportedly used by the received Data 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, as defined in Table 9-7. This parameter is invalid 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, as described in 9.4.4.2. This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00 or 0x01.
KeyIndex	Integer	0x01–0xff	The index of the key purportedly used by the originator of the received frame, as described in 9.4.4.3. This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.
AckSent	Boolean	TRUE, FALSE	TRUE if the received frame requested an acknowledgment that has been sent, FALSE otherwise.
RangingReport-Descriptor	Structure	As defined in Table 8-90a.	Reports ranging related results. The parameter is invalid if ranging is not supported or not enabled.

Table 8-90—MCPS-DATA.indication parameters *(continued)*

Name	Type	Valid range	Description
~~RangingReceived~~	~~Enumeration~~	~~NO_RANGING_REQUESTED, RANGING_ACTIVE, RANGING_REQUESTED_BUT_NOT_SUPPORTED~~	~~A value of RANGING_REQUESTED_BUT_NOT_SUPPORTED indicates that ranging is not supported but has been requested. A value of NO_RANGING_REQUESTED indicates that no ranging is requested for the PSDU received. A value of RANGING_ACTIVE denotes ranging operations requested for this PSDU. A value of NO_RANGING_REQUESTED is used for PHYs that do not support ranging.~~
~~RangingCounterStart~~	~~Unsigned Integer~~	~~As defined in Table 8-89~~	~~As defined in Table 8-89.~~
~~RangingCounterStop~~	~~Unsigned Integer~~	~~As defined in Table 8-89~~	~~As defined in Table 8-89.~~
~~RangingTrackingInterval~~	~~Integer~~	~~As defined in Table 8-89~~	~~As defined in Table 8-89.~~
~~RangingOffset~~	~~Signed Magnitude Integer~~	~~As defined in Table 8-89~~	~~As defined in Table 8-89.~~
~~RangingFom~~	~~Integer~~	~~As defined in Table 8-89~~	~~As defined in Table 8-89.~~
~~AngleOfArrivalAzimuth~~	~~Float~~	~~–π to +π~~	~~Angle of arrival of signal in azimuth measured in radians. This parameter is valid only when AngleOfArrivalSupported is set to either AZIMUTH, or BOTH. The real world direction indicated (e.g., by 0 radians) is a system set-up parameter beyond the scope of this standard.~~
~~AngleOfArrivalElevation~~	~~Float~~	~~–π/2 to +π/2~~	~~Angle of arrival of signal in elevation measured in radians. This parameter is valid only when AngleOfArrivalSupported is set to either ELEVATION, or BOTH.~~
~~AngleOfArrivalSupported~~	~~Enumeration~~	~~NONE, BOTH, AZIMUTH, ELEVATION~~	~~Indicates validity of AngleOfArrivalAzimuth and AngleOfArrivalElevation. Where the underlying PHY does not support angle of arrival measurement, then this parameter shall be set to NONE.~~
DataRate	Integer	—	As defined in Table 8-88.
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.

Insert new text and Table 8-90a at the end of 8.3.4 as follows:

The elements of the RangingReportDescriptor structure are defined in Table 8-90a. 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 of an Ack frame was not sent.

Table 8-90a—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 6.9.1.4.
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 6.9.1.4.
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 6.9.1.6.3. 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 6.9.1.6.2. 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 6.9.1.7.
AngleOfArrivalAzimuth	Float	–π to +π	When *macAoaEnable* 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.
AngleOfArrivalElevation	Float	–π/2 to +π/2	When *macAoaEnable* 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.

Table 8-90a—Elements of the RangingReportDescriptor *(continued)*

Name	Type	Valid range	Description
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 6.9.1.4. 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 6.9.1.4. 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 6.9.1.4. 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 6.9.1.4. 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 6.9.1.4. 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 6.9.1.4. 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 6.9.1.4. This value is invalid if the SRMARKER1 was not sent.
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 6.9.1.4. This value is invalid if the SRMARKER2 was not sent.

Table 8-90a—Elements of the RangingReportDescriptor *(continued)*

Name	Type	Valid range	Description
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 6.9.1.4. 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 6.9.1.4. 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.
RangingStsAoaAzimuth-Fom	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.
RangingStsAoaElevation-Fom	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.

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 RFRAME; the RxS0RangingCounter, RxS1RangingCounter, and RangingStsFom (for STS segment 1) elements of the RangingReportDescriptor (defined in Table 8-90a) 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 "Applications of IEEE Std 802.15.4" [B3].

Insert new subclauses 8.3.7 and 8.3.8 after 8.3.6 as follows:

8.3.7 ACRR verifier primitives

8.3.7.1 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,
                                AcrrcIeIncluded,
                                AddressMask,
                                SrcAddrMode,
                                DstAddrMode,
                                DstPanId,
                                DstAddr,
                                SecurityLevel,
                                KeyIdMode,
                                KeySource,
                                KeyIndex,
                                DistanceCommitmentLevel,
                                UwbPreambleSymbolRepetitions,
                                DataRate,
                                LocationEnhancingInformationPostamble,
                                LocationEnhancingInformationPostambleLength,
                                PanIdSuppressed,
                                SeqNumSupressed
                                )
```

The primitive parameters are defined in Table 8-92a.

Table 8-92a—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: TimeOut × *phyLrpUwbFixedReplyTime*
AcrrMode	Integer	0–3	Selects the ACRR mode as specified Table 7-52m.
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.

Table 8-92a—MCPS-RANGING-VERIFIER.request parameters *(continued)*

Name	Type	Valid range	Description
ChallengeLength	Integer	As per 7.5.31	Specifies the length in octets of the challenge to be used by the MAC sublayer when RawMode is set to TRUE.
AcrrcIeIncluded	Boolean	TRUE, FALSE	If TRUE, the MAC sublayer generates an ACRRC IE and transmits it within the command frame. The content of the ACRRC IE shall correspond to the values indicated in the AcrrMode and SecurityLevel 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.
SecurityLevel	Integer	As defined in Table 8-88	As defined in Table 8-88.
KeyIdMode	—	As defined in Table 8-88	As defined in Table 8-88.
KeySource	Set of octets	As defined in Table 8-88	As defined in Table 8-88.
KeyIndex	Integer	As defined in Table 8-88	As defined in Table 8-88.
DistanceCommit-mentLevel	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 $T_{\text{int,RF}}$ as a fraction of an RSTU as per the definition in 10.3.2.
UwbPreambleSymbol-Repetitions	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 8-1. For all other PHYs, the parameter is set to zero.
LocationEnhancingInfor-mationPostamble	Enumeration	As defined in Table 8-88	As defined in Table 8-88.

Table 8-92a—MCPS-RANGING-VERIFIER.request parameters *(continued)*

Name	Type	Valid range	Description
LocationEnhancingInformationPostambleLength	Enumeration	As defined in Table 8-88	As defined in Table 8-88.
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 8-92a. Setting these parameters depends on the ACRR mode and it is described in 6.9.8 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 7.5.31) 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.

8.3.7.2 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 8-92b.

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 a MCPS-RANGING-VERIFIER.indication primitive or when a timeout has occurred as shown in Figure 6-48z6 and Figure 6-48z7.

Table 8-92b—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.

8.3.7.3 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,
                                  HeaderIeList,
                                  PayloadIeList,
                                  SecurityLevel,
                                  KeyIdMode,
                                  KeySource,
                                  KeyIndex,
                                  RangingStatus,
                                  RangingSecurityLevel,
                                  RangingReportDescriptor,
                                  Rssi,
                                  RangingChallenge,
                                  RangingResponse
                                  )
```

The primitive parameters are defined in Table 8-92c.

Table 8-92c—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.

Table 8-92c—MCPS-RANGING-VERIFIER.indication parameters *(continued)*

Name	Type	Valid range	Description
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.
HeaderIeList	As per Table 8-90.	As defined in Table 8-90	As defined in Table 8-90.
PayloadIeList	As per Table 8-90.	As defined in Table 8-90	As defined in Table 8-90.
SecurityLevel	Integer	As defined in Table 8-90	As defined in Table 8-90.
KeyIdMode	Integer	As defined in Table 8-90	As defined in Table 8-90.
KeySource	Set of octets	As defined in Table 8-90	As defined in Table 8-90.
KeyIndex	Integer	As defined in Table 8-90	As defined in Table 8-90.
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.
RangingSecuri-tyLevel	Integer	0x00–0x07	Provides the security level, (as defined in Table 9-6). used by the MAC security services during the ranging exchange when an ACRRC IE is used.
RangingReport-Descriptor	Structure	As defined in Table 8-90a	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.
RangingChal-lenge	Set of octets	As defined in 7.5.31	Payload send by the verifier with Ranging Verifier command.
RangingRe-sponse	Set of octets	As defined in 7.5.32	Payload send by the prover with Ranging Prover 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 8-92c.

8.3.8 ACRR prover primitives

8.3.8.1 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,
                               SecurityLevel,
                               KeyIdMode,
                               KeySource,
                               KeyIndex,
                               DistanceCommitmentLevel,
                               UwbPreambleSymbolRepetitions,
                               DataRate,
                               LocationEnhancingInformationPostamble,
                               LocationEnhancingInformationPostambleLength,
                               PanIdSuppressed,
                               SeqNumSupressed
                               )
```

The primitive parameters are defined in Table 8-92d.

Table 8-92d—MCPS-RANGING-PROVER.request parameters

Name	Type	Valid range	Description
TimeOut	Integer	0x000000–0xffffff	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: TimeOut × *phyLrpUwbFixedReplyTime.*
AcrrMode	Integer	0–3	Selects the ACRR mode as specified Table 7-52m.
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.

Table 8-92d—MCPS-RANGING-PROVER.request parameters *(continued)*

Name	Type	Valid range	Description
ResponseLength	Integer	As per 7.5.32	Specifies the length in octets of the response to be used by the MAC sublayer when RawMode is set to TRUE.
AcrrcIeIncluded	Boolean	TRUE, FALSE	If TRUE, the MAC sublayer generates an ACRRC IE and transmits it within the command frame. The content of the ACRRC IE shall correspond to the values indicated in the AcrrMode and SecurityLevel parameters.
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.
SecurityLevel	Integer	As defined in Table 8-88	As defined in Table 8-88.
KeyIdMode	—	As defined in Table 8-88	As defined in Table 8-88.
KeySource	Set of octets	As defined in Table 8-88	As defined in Table 8-88.
KeyIndex	Integer	As defined in Table 8-88	As defined in Table 8-88.
DistanceCommit-mentLevel	Enumeration	As defined in Table 8-92a	As defined in Table 8-92a.
UwbPreambleSymbol-Repetitions	Integer	As defined in Table 8-88	As defined in Table 8-88.
DataRate	Integer	—	Indicates the data rate. For LRP UWB PHYs, valid values are defined in Table 18-1. For all other PHYs, the parameter is set to zero.
LocationEnhancingInfor-mationPostamble	Enumeration	As defined in Table 8-88	As defined in Table 8-88.
LocationEnhancingInfor-mationPostambleLength	Enumeration	As defined in Table 8-88	As defined in Table 8-88.
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 8-92d. The choice of parameter values depends on the ACRR mode as described in 6.9.8 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 7.5.32).

In multi-node ranging the prover replies to the broadcast address as described in 6.9.8.4.8.

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.

8.3.8.2 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 8-92e.

Table 8-92e—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 a MCPS-RANGING-VERIFIER.indication primitive and expiration of the fixed reply time timer or when a timeout has occurred as shown in Figure 6-48z6.

8.3.8.3 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,
                                  HeaderIeList,
                                  PayloadIeList,
```

SecurityLevel,
KeyIdMode,
KeySource,
KeyIndex,
RangingReportDescriptor,
Rssi,
RangingSecurityLevel,
RangingChallenge,
RangingResponse
)

The primitive parameters are defined in Table 8-92f.

Table 8-92f—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 8-90	As defined in Table 8-90	As defined in Table 8-90.
PayloadIeList	As per Table 8-90	As defined in Table 8-90	As defined in Table 8-90.
SecurityLevel	Integer	As defined in Table 8-90	As defined in Table 8-90.
KeyIdMode	Integer	As defined in Table 8-90	As defined in Table 8-90.
KeySource	Set of octets	As defined in Table 8-90	As defined in Table 8-90.
KeyIndex	Integer	As defined in Table 8-90	As defined in Table 8-90.
RangingReportDescriptor	Structure	As defined in Table 8-90a	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.

Table 8-92f—MCPS-RANGING-PROVER.indication parameters *(continued)*

Name	Type	Valid range	Description
RangingSecurityLevel	Integer	As defined in Table 8-92c	As defined in Table 8-92c.
RangingChallenge	Set of octets	As defined in 7.5.27	Payload send by the verifier with Ranging Verifier command.
RangingResponse	Set of octets	As defined in 7.5.28	Payload send by the prover with Ranging Prover command.

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 8-92f.

8.4 MAC constants and PIB attributes

8.4.3 MAC PIB attributes

8.4.3.1 Overview

Change the row for "macFcsType" and insert a new row for "macAoaEnable" in Table 8-94 as follows (unchanged rows not shown):

Table 8-94—MAC PIB attributes

Attribute	Type	Range	Description	Default
…				
macFcsType	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, and SUN PHYs<u>, and the HRP UWB PHY in HPRF mode</u>.	0
…				
macAoaEnable	Boolean	FALSE, TRUE	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
…				

10. General PHY requirements

10.1 General

10.1.2 Operating frequency range

Change the row for "LRP UWB" in Table 10-1 as follows (unchanged rows not shown):

Table 10-1—Frequency band designations

Band designation (MHz)	Frequency band (MHz)
…	
LRP UWB	~~6289.6–9185.6~~ 5624.32–10 435.2

10.1.3 Channel assignments

10.1.3.8 Channel numbering for LRP UWB PHY

Change 10.1.3.8 as follows:

The LRP UWB PHY uses channel page eight with the channel numbers defined in Table 10-13. A total of ~~three~~ ten frequency channels~~, numbered 0 to 2,~~ are available in the ~~6289.6~~ 5624.32 MHz to ~~9185.6~~ 10 435.2 MHz frequency bands. Different subsets of these frequency channels are available in different regions of the world. ~~In North America and Europe, a shared channel may be used.~~

Table 10-13—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
7	8640.0
8	9292.8
9	9945.6

10.2 General radio specifications

10.2.8 Clear channel assessment (CCA)

Change the dashed list entry "CCA Mode 5:" in 10.2.8 as follows:

— *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 15.2.6 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 higher pulse repetition frequency (HPRF) mode, and to receive its acknowledgment. ~~CCA shall report a busy medium upon detection of a preamble symbol as specified in 15.2.6. An idle channel shall be reported if no preamble symbol is detected up to a period not shorter than the maximum packet duration plus the maximum period for acknowledgment.~~

Insert new subclause 10.3 after 10.2 as follows:

10.3 Ranging capable PHY

10.3.1 General

This subclause applies for devices that have implemented ranging support (RDEVs).

10.3.2 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 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 10-2 illustrates the distance commitment principle.

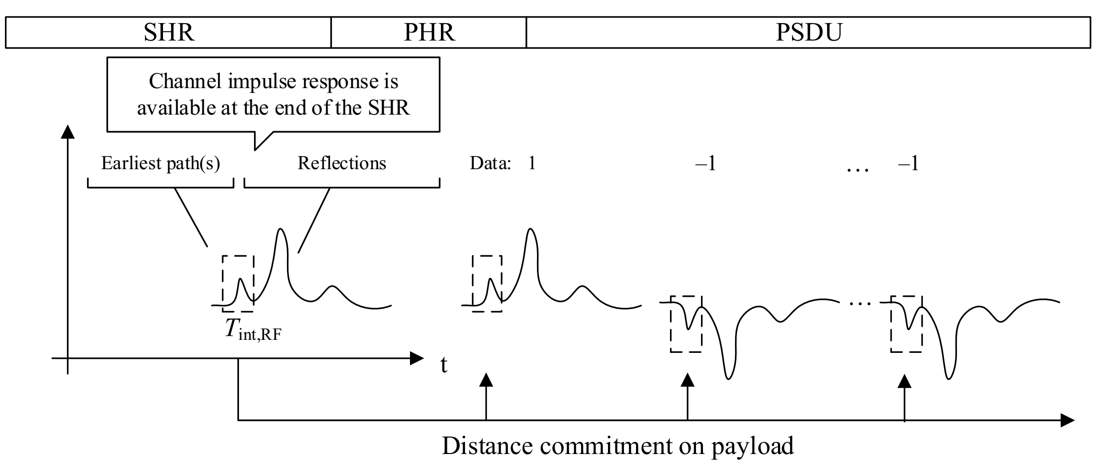

Figure 10-2—Distance commitment principle and RF integration window

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 “Applications of IEEE Std 802.15.4” [B3].

Under distance commitment operation at the receiver, the time of arrival and the energy integration window $T_{\mathrm{int,RF}}$ shall be used for PSDU symbol decoding. The aperture $T_{\mathrm{int,RF}}$ is the allowed window duration for collecting and integrating the incoming RF energy at the receiver. Distance commitment ensures that the 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 10-26. Relevant implementation guidelines are provided in Section 2 of “Authenticated Ranging of IEEE 802.15.4” [B20a].

NOTE—Although Figure 10-2 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).

Table 10-26—Distance commitment level definition for authenticated ranging

DistanceCommitmentLevel	$T_{\mathrm{int,RF}}$ aperture time (RSTU)	Maximum PSDU symbol distance offset from RMARKER (c_0 = 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

The MCPS-RANGING-VERIFIER and MCPS-RANGING-PROVER primitives include the DistanceCommitmentLevel parameter to set the value of the aperture $T_{\mathrm{int,RF}}$.

11. PHY services

11.2 PHY constants

Change the row for "aMaxPhyPacketSize" in Table 11-1 as follows (unchanged rows not shown):

Table 11-1—PHY constants

Constant	Description	Value
aMaxPhyPacketSize	The maximum PSDU size (in octets) the PHY shall be able to receive.	2047 for the following PHYs: SUN, TVWS, RCC, LECIM FSK, and MSK with a 2000 kb/s data rate. For LECIM DSSS PHY, this is not a constant; refer to *phyLecimDsssPsduSize*. For the HRP UWB PHY, this is not a constant; refer to *phyHrpUwbPsduSize*. 127 for all other PHYs.
…		

11.3 PHY PIB attributes

Change the row for "phyCurrentCode" in Table 11-2 and insert new rows at the end of the table as follows (unchanged rows not shown):

Table 11-2—PHY PIB attributes

Attribute	Type	Range	Description
…			
phyCurrentCode	Integer	~~0–24~~ 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 15-6, ~~and~~ Table 15-7, and Table 15-7a. For the CSS PHY, the value indicates the subchirp, as defined in 14.3.
…			
phyLrpUwbFixedDelayFactor	Integer	1 to 32 767	Define the reply delay factor that multiplies the *phyLrpUwbFixedReplyTime* to be used in multi-node ranging.
phyLrpUwbFixedReplyTime	Enumeration	FRT4, FRT8, FRT16, FRT32	For LRP-ERDEV this attribute selects the fixed reply time as specified in Table 18-11.
phyFixedReplyTimeSupported†	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.

Table 11-2—PHY PIB attributes *(continued)*

Attribute	Type	Range	Description
phyHrpUwbCcConstraintLength	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 15.3.3.3. When not in HPRF mode, the constraint length shall be 3 and this attribute shall be ignored.
phyHrpUwbPhrA0	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 15.2.7.3.
phyHrpUwbPhrA1	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 15.2.7.3.
phyHrpUwbPhrDataRate	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 15-9a and Table 15-10b.
phyHrpUwbPsduSize	Integer	0 to 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 15.2.7.3 and Table 15-9c.
phyHrpUwbPsr	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 15.2.6.2.
phyHrpUwbSfdSelector	Integer	0 to 4	This attribute selects the SFD pattern to be used by the transmitter and receiver, as specified in 15.2.6.3 and Table 15-7c.
phyHrpUwbStsKey	16 octets	—	This attribute specifies the STS key 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.
phyHrpUwbStsPC2RxGap0	Integer	0 to 127	When *phyHrpUwbStsRxPacketConfig* 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 15-9b.
phyHrpUwbStsPC2RxGap1	Integer	0 to 127	When *phyHrpUwbStsRxPacketConfig* 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 15-9b.

Table 11-2—PHY PIB attributes *(continued)*

Attribute	Type	Range	Description
phyHrpUwbStsPC2RxGap2	Integer	0 to 127	When *phyHrpUwbStsRxPacketConfig* 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 15-9b.
phyHrpUwbStsPC2RxGap3	Integer	0 to 127	When *phyHrpUwbStsRxPacketConfig* 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 15-9b.
phyHrpUwbStsPC2TxGap	Integer	0 to 127	When *phyHrpUwbStsTxPacketConfig* 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 15.2.7.3.
phyHrpUwbStsRxPacketConfig†	Integer	0 to 3	This attribute indicates the presence and position of the STS field in the PPDU expected by the receiver, as per Table 15-a.
phyHrpUwbStsRxSegLen†	Integer	0 to 3	This attribute indicates the length of active STS segment(s) in the PPDU expected by the receiver, as specified in Table 15-9e.
phyHrpUwbStsRxSegNum†	Integer	0 to 3	This attribute indicates the number of STS segments in the PPDU expected by the receiver, as specified in Table 15-9e.
phyHrpUwbStsTxPacketConfig†	Integer	0 to 3	This attribute indicate the presence and position of the STS field in the transmitted PPDU as per Table 15-a.
phyHrpUwbStsTxSegLen†	Integer	0 to 3	This attribute indicates the length of active STS segment(s) in the transmitted PPDU, as specified in Table 15-9e.
phyHrpUwbStsTxSegNum†	Integer	0 to 3	This attribute indicates the number of STS segments in the transmitted PPDU, as specified in Table 15-9e.
phyHrpUwbStsVCounter	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 15.2.9. 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.
phyHrpUwbStsVUpper96	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 15.2.9. This attribute shall not be modified during packet transmission or reception.
phyLrpUwbPrp	Integer	0 to 7	Selects the pulse repetition period (PRP) to used, as specified in 18.2.6. The value corresponds to the factor k_{PRP} defined in Table 18-4b.

Table 11-2—PHY PIB attributes *(continued)*

Attribute	Type	Range	Description
phyLrpUwbSfdSelector	Integer	0 to 9	This attribute selects the SFD pattern to be used by the transmitter and receiver, as specified in 18.3.3.2 and Table 18-4c.
phyLrpUwbSignaling	Integer	0 to 15	For the LRP UWB PHY, when attribute is non-zero, it configures the PHY to receive with the signaling scheme defined in Table 18-1.
phyRxRmarkerOffset	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 6.9.1.4.
phyTxRmarkerOffset	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 6.9.1.4.

15. HRP UWB PHY

15.1 General

Insert new text at the end of 15.1 as follows:

For the HRP UWB PHY, where MAC timing is specified in symbols, the duration of a preamble symbol 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 higher pulse repetition frequency (HPRF) mode.

15.2 HRP UWB PPDU format

15.2.1 General

Insert new text, Table 15-a, and Figure 15-2a at the end of 15.2.1 as follows:

The HRP-ERDEV shall support transmission and reception of packets as specified in Table 15-a. Figure 15-2a provides an informative depiction of the STS position in the PPDU as well as the position of the RMARKER as defined in 6.9.1.

Table 15-a—PPDU STS packet structure configurations

STS packet configuration specifier value (see note)	Selected the 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 15-a applies to the TxStsPacketStructure and RxStsPacketStructure parameters of the MLME-STS.request primitive specified in 8.2.27.1 and to the *phyHrpUwbStsTxPacketConfig* and *phyHrpUwbStsRxPacketConfig* attributes.

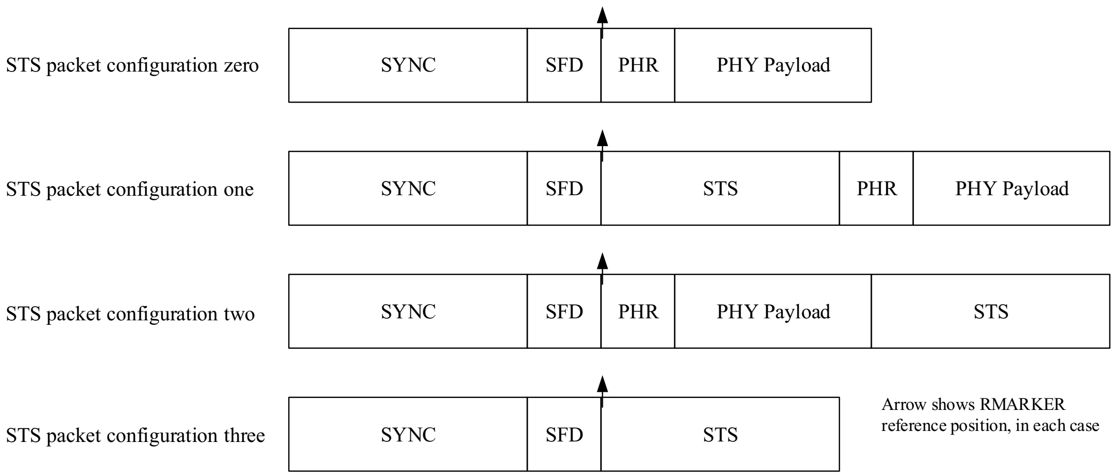

Figure 15-2a—HRP-ERDEV PPDU formats with RMARKER position

15.2.2 PPDU encoding process

Change item d) and insert a new item f) in the lettered list in 15.2.2 as follows:

d) For the HPRF mode, modulate and spread the PHR and PSDU as described in 15.3.4. 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 ~~Modulate~~ and spread PSDU according to the method described in 15.3.1 and 15.3.2,~~.~~ where the ~~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.

…

f) For HRP-ERDEV, produce the STS as described in 15.2.9 according to the setting of the *phyHrpUwbStsTxPacketConfig*, *phyHrpUwbStsTxSegLen*, and *phyHrpUwbStsTxSegNum* attributes.

15.2.6 SHR field

15.2.6.2 SYNC field

Replace Figure 15-5 with the following (corrected) figure:

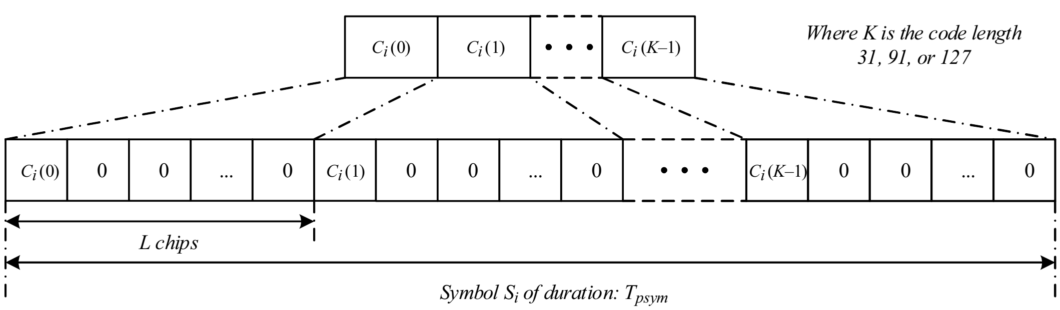

Figure 15-5—Construction of symbol S_i from code C_i

Insert new text, Table 15-7a, and Table 15-7b at the end of 15.2.6.2 as follows:

The HRP-ERDEV shall support the length 91 codes specified in Table 15-7a with the parameters specified in Table 15-7b. 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 15-7b.

Table 15-7a—Length 91 ternary codes for the HRP-ERDEV

Code index	Code sequence
25	– 0 + + + + – – + – – + – + + + + – + – – – + + – – + + + + + + – + + – + 0 0 + – – + 0 – – + 0 + + + + + – – + + + – – 0 – – 0 + – + – – – – 0 – + – + – + 0 + – – + + – + – + + + 0
26	+ + 0 + – + – – – + + + + + – + – + + – – + – – + + – – – + – 0 + + + 0 – + + + + – + 0 + 0 – – 0 + – + + – + + + + + + – – + – + + 0 0 + + + – – 0 + – – – – – + – 0 + – + – + – – –
27	+ + + – – + + + – – – + – + – 0 – + – – 0 + + – + – + 0 – + + + + + + + + + + – – + – – + + – + + 0 + + – + – + – – + – – + + + – – – 0 – + + + – 0 + 0 0 – – – + + – + – – 0 – + + 0
28	+ + + + + – – + + + – + + – – – + – + – – 0 + + – – – + – + 0 + – – – – – + 0 + + + – – + – + – – + – + + – + + + + 0 – 0 – + + 0 0 + – + + + – + + – + 0 – + 0 – – + – – – + + + 0 +
29	+ – 0 – – + – + + – – 0 + + 0 0 + + – + + – – – – – + + + + + + – 0 + – – + – + + – – + – + + + – – + + + + + + + – + + + 0 + – + – 0 – 0 – + + – – – + 0 – – – + + 0 – + – + – + + –
30	– + + 0 – – 0 + + – 0 0 – – + + – + + – + – – + + + + + – – – + + + – + – 0 + – + – + 0 + + + + + – + + + – + + + – + 0 – – – – – – + + – + + – + 0 – – – – + – + – 0 + 0 + – + + + –
31	– + – + + 0 + + + – – + + – 0 + + 0 0 – – + + – – + + + – + – – – – – – 0 + + + – + + + + + – – + – + + – – – + – + – – – + – + 0 – + – – 0 + 0 + – + + – + + 0 + – + – – 0 + + + + +
32	– + + + + + + + + + + + – – – + – + + – – + + 0 0 – + – + 0 – + – 0 – + + – – + + + – + + + 0 – – 0 + + – + – + – 0 – – – + + – 0 – – – – + + + + – + – 0 + 0 – + – + + – + + – – + –

Table 15-7b—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.

15.2.6.3 SFD field

Insert new text and Table 15-7c at the end of 15.2.6.3 as follows:

In the BPRF mode, the HRP-ERDEV shall support the length 8 SFD specified in Table 15-7c (i.e., for the *phyHrpUwbSfdSelector* value of 2) and shall also support the short SFD given in the paragraph above.[5]

[5]This is referring to text in the base standard IEEE Std 802.15.4-2020.

Table 15-7c—SFD sequences for the HRP-ERDEV

SFD #, value of the *phyHrpUwbSfdSelector* 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 –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 –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 15-7c for the *phyHrpUwbSfdSelector* values of 1, 2, and 3. Support of the length 32 SFD specified in Table 15-7c is optional.

In each case the SFD specified in Table 15-7c is spread by the preamble symbol S_i, where the leftmost bit of the SFD shall be transmitted first in time.

15.2.7 PHR field

Insert a new subclause heading 15.2.7.1 to contain the existing text, figure, and tables from 15.2.7 as follows:

15.2.7.1 General

Insert new subclauses 15.2.7.2 and 15.2.7.3 after 15.2.7.1 (formerly the content of 15.2.7) as follows:

15.2.7.2 PHR field for HRP-ERDEV in BPRF mode

In the BPRF mode, the HRP-ERDEV shall use the PHR as specified in 15.2.7.1. 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 15-9a.

Table 15-9a—PHR and PSDU bit rates for the HRP-ERDEV in BPRF mode

Value of the *phyHrpUwbPhrDataRate* 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

15.2.7.3 PHR field for HRP-ERDEV in HPRF mode

In the HPRF mode, the HRP-ERDEV shall use the PHR format as shown in Figure 15-6a. This is transmitted without Reed-Solomon coding. Both PSDU and PHR shall use the same convolutional code and modulation as described in 15.3.4.

Bits: 0	1	2–11	12	13–18
A1	A0	PHY payload length	Ranging	SECDED

Figure 15-6a—HRP-ERDEV HPRF mode PHY header

This PHR includes the Ranging and SECDED fields encoded as specified in 15.2.7.1, 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 15-1.

In the optional PPDU format where the STS follows the payload, as selected by STS packet configuration value of 2 (in Table 15-a), 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 15-9b. It is the responsibility of the higher layers to ensure that A1 and A0 are correctly set in the PHR, using the *phyHrpUwbPhrA0* and *phyHrpUwbPhrA1* attributes, and that the appropriate *phyHrpUwbStsPC2TxGap* is set to correctly align with the remote receiver's configuration of the attributes in Table 15-9b.

Table 15-9b—Optional payload to STS gap

A1	A0	Gap (chips)
0	0	*phyHrpUwbStsPC2RxGap0*
0	1	*phyHrpUwbStsPC2RxGap1*
1	0	*phyHrpUwbStsPC2RxGap2*
1	1	*phyHrpUwbStsPC2RxGap3*

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 15-9c. Since the PSDU length is determined by the MCPS-DATA.request primitive, the *phyHrpUwbPhrA0* and *phyHrpUwbPhrA1* attributes are used/ignored as specified in Table 15-9c.

Table 15-9c—HPR-ERDEV maximum PSDU length extension

Value of the *phyHrpUwbPsduSize* 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 *phyHrpUwbPhrA0* 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 *phyHrpUwbPhrA0* and *phyHrpUwbPhrA1* attributes are ignored.

15.2.8 PHY Payload field

Change the last item in the dashed list in 15.2.8 as follows:

— For the HRP-ERDEV in its HPRF mode, spread and modulate the encoded block as described in 15.3.4, otherwise spread ~~Spread~~ and modulate the encoded block using BPM-BPSK modulation as described in 15.3.

Insert new subclause 15.2.9 after 15.2.8 as follows:

15.2.9 Scrambled timestamp sequence (STS) field

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 (~1 µs). Figure 15-7a shows the extent of the STS when consisting of one or two segments. Table 15-9d specifies the numbers of segments and the segment lengths that shall be supported.

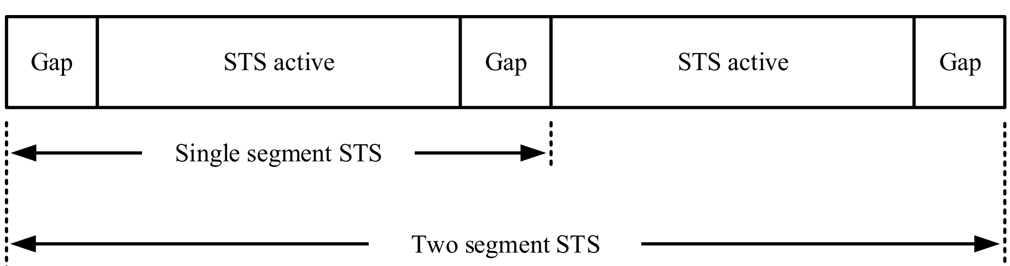

Figure 15-7a—STS segments

In the optional PPDU format where the STS follows the payload, (i.e., STS packet configuration value of 2 in Table 15-a), an optional additional gap as specified by the *phyHrpUwbStsPC2TxGap* attribute shall be inserted between the PSDU and the STS.

15.2.9.1 The STS generation DRBG

The STS shall be generated using a DRBG with the structure shown in Figure 15-7b. This is using 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 15.2.9.2. 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.

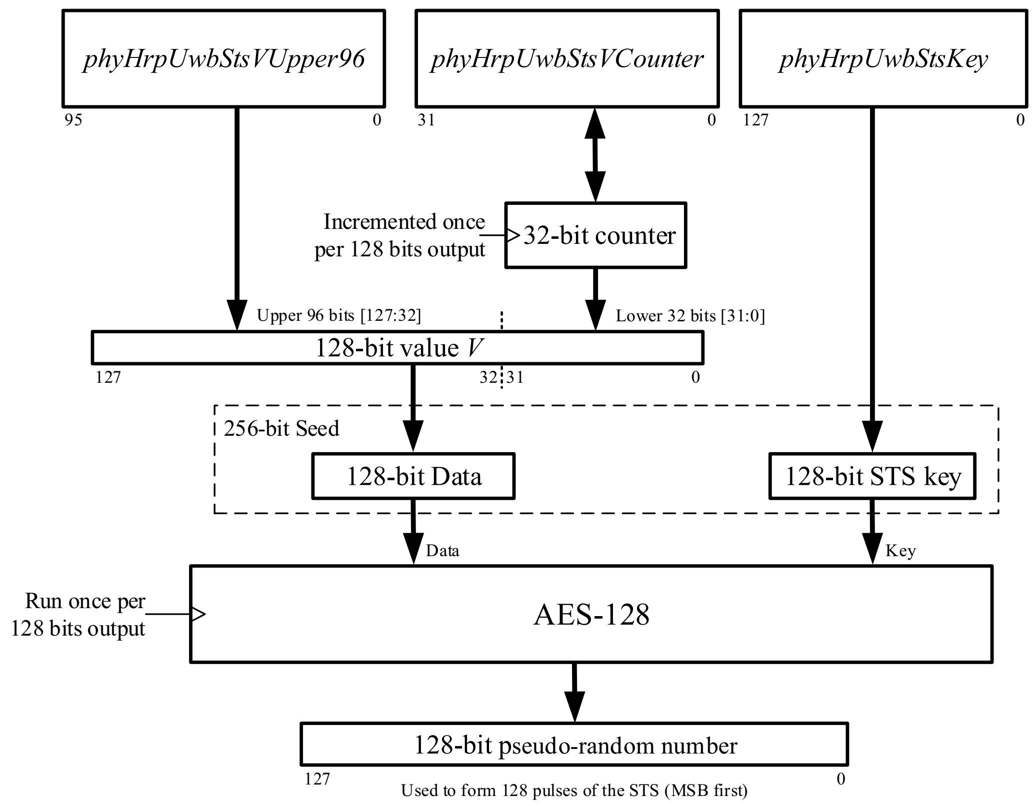

Figure 15-7b—DRBG for STS

The higher layer is responsible for setting the 128-bit STS key, via the *phyHrpUwbStsKey* 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 H.

While this specification covers the transmitter operation, it is expected that the receiver will use the same mechanism and aligned values of the STS key 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 RSKD IE described in 7.4.4.42 may be used to synchronize the values of *V* and the STS key between HRP-ERDEVs before they participate in a ranging exchange employing the STS.

15.2.9.2 Forming the STS

Each iteration of the DRBG specified in 15.2.9.1 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 15.2.6.2 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 15-9d along with the number of segments and the segment lengths that shall be supported. Figure 15-7a 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 15-9e and Table 15-9f define the configuration options for segment length and number of segments in the STS.

Table 15-9d—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 15-9e—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 15-9e applies to the TxStsSegmentLength and RxStsSegmentLength parameters of the MLME-STS.request primitive specified in 8.2.27.1 and to the *phyHrpUwbStsTxSegLen* and *phyHrpUwbStsRxSegLen* attributes.

Table 15-9f—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 15-9f applies to the TxStsNumberSegments and RxStsNumberSegments parameters of the MLME-STS.request primitive specified in 8.2.27.1 and to the *phyHrpUwbStsTxSegNum* and *phyHrpUwbStsRxSegNum* attributes.

15.2.9.3 Additional STS RMARKERs

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 15-7c. 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.

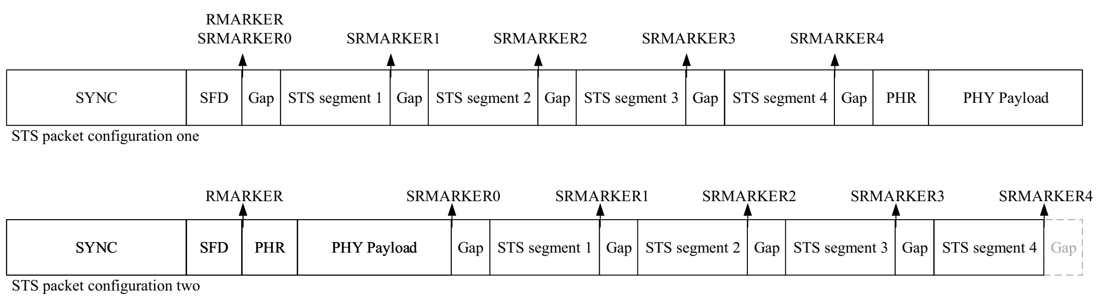

Figure 15-7c—Position of STS SRMARKERs

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.

15.3 Modulation

15.3.3 FEC

Change the title and content of 15.3.3.3 as follows:

15.3.3.3 ~~Systematic convolutional~~ Convolutional encoding

The inner convolutional encoder shall use the $K = 3$ rate $R = ½$ code with generator polynomials $g_0 = [010]_2$ and $g_1 = [101]_2$, as shown in Figure 15-11. 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 that since the generator polynomials are systematic, they are also noncatastrophic.

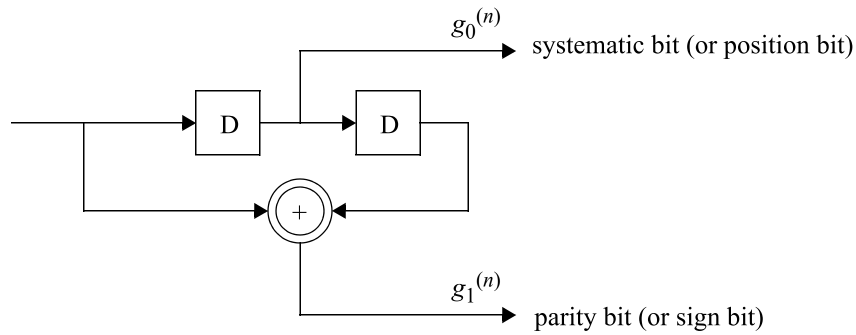

Figure 15-11—*K* = 3 s~~S~~ystematic convolutional encoder

Insert new text and Figure 15-11a at the end of 15.3.3.3 as follows:

The HRP-ERDEV in its HPRF mode may optionally employ the $K = 7$ convolutional encoder, with the generator polynomials (133,171), as shown in Figure 15-11a. 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 15.3.3.2 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.

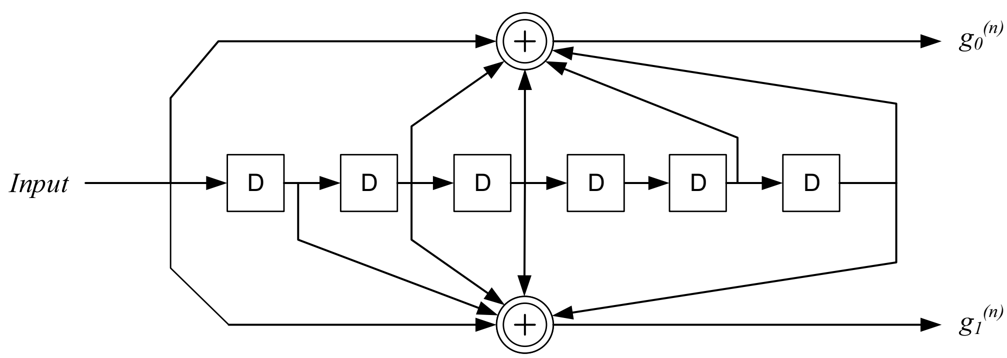

Figure 15-11a—Optional HRP-ERDEV *K* = 7 convolutional encoder

Insert new subclause 15.3.4 after 15.3.3 as follows:

15.3.4 HRP-ERDEV modulation in HPRF mode

15.3.4.1 Introduction

The HRP-ERDEV in its HPRF mode shall support both modulations described in 15.3.4.2 and 15.3.4.3. The modulation parameters of these are summarized in Table 15-10a.

Table 15-10a—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 15.3.4.2 and 15.3.4.3. 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 15-10b.

Table 15-10b—PHR and PSDU data rates for the HRP-ERDEV in HPRF mode

Value of the *phyHrpUwbPhrDataRate* attribute	Value of the *phyHrpUwbCcConstraintLength* 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

15.3.4.2 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 15-11b 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 15-11c.

When employing the optional HRP-ERDEV convolutional encoder, the data modulation shown in Figure 15-11b shall apply to both PHR and PSDU.

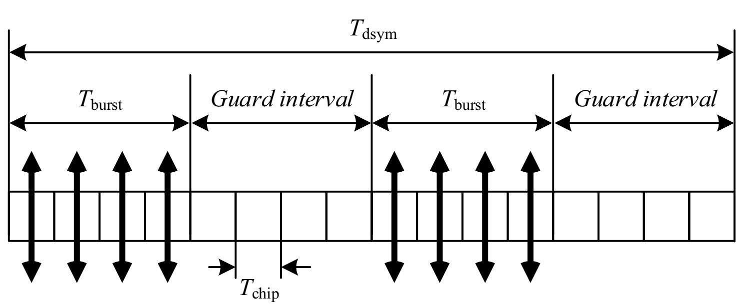

Figure 15-11b—HRP-ERDEV data symbol structure at 249.6 MHz PRF

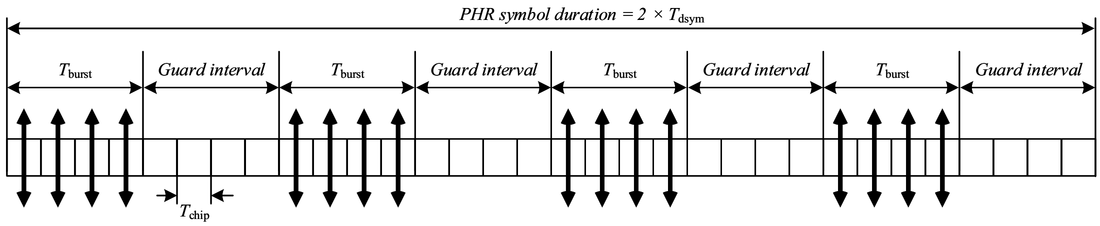

Figure 15-11c—HRP-ERDEV PHR symbol structure at 249.6 MHz PRF

The $g_0^{(n)}$ and $g_1^{(n)}$ output of the convolutional encoder specified in 15.3.3.3 shall be mapped onto the burst bit patterns specified in Table 15-10c and scrambled by the time-varying spreading code s_n as specified in 15.3.2 before being sent as pulses as per 15.3.1, (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 15-10d.

Table 15-10c—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 15-10d—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.

15.3.4.3 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 15-11d, 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 15-11e.

When employing the optional HRP-ERDEV convolutional encoder, the data modulation shown in Figure 15-11d shall apply to both PHR and PSDU.

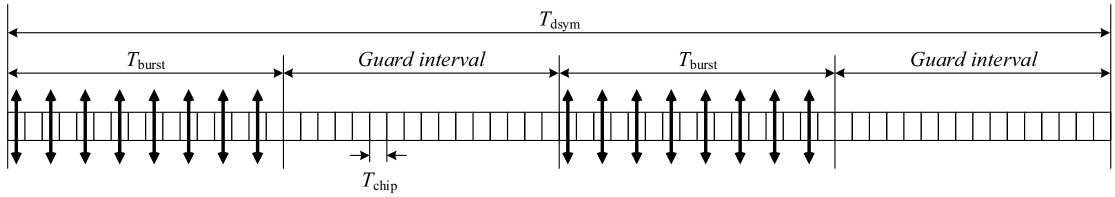

Figure 15-11d—HRP-ERDEV data symbol structure at 124.8 MHz PRF

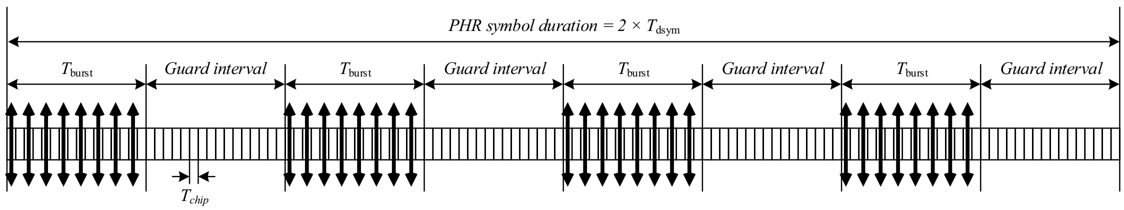

Figure 15-11e—HRP-ERDEV PHR symbol structure at 124.8 MHz PRF

The $g_0^{(n)}$ and $g_1^{(n)}$ output of the convolutional encoder specified in 15.3.3.3 shall be mapped onto the burst bit patterns specified in Table 15-10e and scrambled by the time-varying spreading code s_n as specified in 15.3.2 before being sent as pulses as per 15.3.1, (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 15-10f.

Table 15-10e—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 0
1	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	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 15-10f—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 0
1	0	1 1 1 1 1 1 1 1	0 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.

15.4 RF requirements

15.4.4 Baseband impulse response

Insert new text and Figure 15-13a at the end of 15.4.4 as follows:

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. In Figure 15-13, the middle pulse has precursors while the left-hand pulse has no precursors. Note that this is not suggesting that either of these particular pulses are recommended.

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 15-13a, where the peak magnitude of the pulse is scaled to a value of one, and the time unit is T_p, defined in Table 15-12. 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.

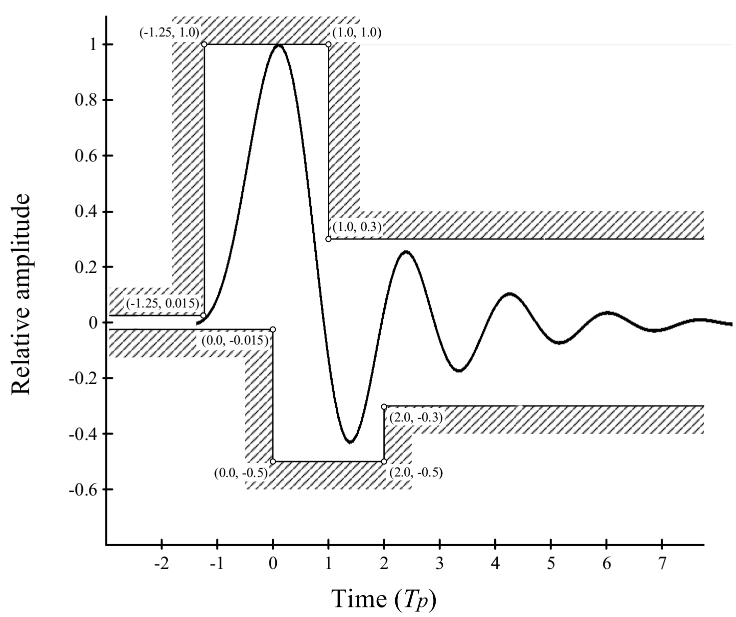

Figure 15-13a—Recommended time domain mask for the HRP UWB PHY pulse

15.4.6 Chip rate clock and chip carrier alignment

Change 15.4.6 as follows:

An HRP UWB transmitter shall be capable of chipping at the peak PRF given in Table 15-3 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 15-11 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.

Delete 15.7 including Figure 15-18 and Table 15-15 through Table 15-18.

Insert a new subclause 15.7 after 15.6 as follows:

15.7 HRP-ERDEV parameter sets

The HRP-ERDEV includes a number of mandatory elements, combinations of which represent a large set of operating modes. Table 15-15 and Table 15-16 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 15-15—Mandatory BPRF mode operating parameter sets

BPRF set #	SYNC PSR	SFD # per Table 15-7c	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	
3	64	2	8	1	64	Yes	6.8	STS packet configuration 1: 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 15-15, 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 15.2.7.2), and shall support the preamble symbol codes for the code index values of 9, 10, 11, and 12 specified in Table 15-7.

Table 15-16—Mandatory HPRF mode operating parameter sets

HPRF set #	SYNC PSR	SFD # per Table 15-7c	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	
5	64	2	8	2	32	Yes	6.8	
6	64	2	8	1	64	Yes	6.8	STS packet configuration 1: SHR, STS, PHR and Data (lower data rate)
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	STS packet configuration 1: SHR, STS, PHR and Data (higher data rate)
15	32	2	8	2	64	Yes	27.2	
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 15-16, 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 15.2.7.3), and shall support all the preamble symbol codes specified in Table 15-7a. The HRP-ERDEV should furthermore support an HPRF operating mode where the SYNC PSR is 32, the SFD # per Table 15-7c 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 [Ba] with a description of these in [B6a].

18. LRP UWB PHY specification

18.1 Overview

Change the text of 18.1 as follows:

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 waveform is based upon an impulse radio signaling scheme using band-limited data pulses. It consists of three frequency channels and occupies the spectrum from 6.2896 GHz to 9.1856 GHz. A combination of on-off keying (OOK) modulation or pulse position modulation (PPM) is used to support both coherent and noncoherent receivers using a common signaling scheme. Either OOK or PPM are used to modulate the symbols, as defined by the mode. Symbols are composed of one or more active bursts of UWB pulses. The various data rates are supported through the use of variable-length bursts.~~

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 PRP provides reduced co-interference between separate networks.

The LRP UWB PHY defines ~~supports~~ the following operation ~~three transmission~~ modes:

— *Base mode*, for base ~~highest~~ 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 ~~All transmit modes are optional, but all~~ modes shall be implemented in the receiver and ~~operational~~ concurrently operational, while all other transmit and receive modes are optional. Active RFID systems are often simplex systems, so mandatory modes are not defined for the PHY but separately for the transmitter (RFD-TX) and receiver (RFD-RX).

The PHY has different characteristics depending on its operation ~~the transmission~~ mode. These characteristics are defined for each mode separately as shown in Table 18-1. ~~Otherwise, the characteristics of the PHY are independent of transmission mode.~~

Replace Table 18-1 with the following table:

Table 18-1—Signaling modes and data rates for LRP UWB PHY

Mode	Modulation	PRF (MHz)	Pulses per symbol	Data rate	*phyLrpUwbSignaling* 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
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

18.2 LRP UWB PHY symbol structure

18.2.1 Overview

Insert new text at the end of 18.2.1 as follows:

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 18-4a, 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 18-4a, 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 18.2.6

Insert new subclauses 18.2.5 and 18.2.6 after 18.2.4 as follows:

18.2.5 Dual-frequency LRP UWB PHY symbol structure

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 18-4a.

Table 18-4a—PBFSK pulse frequency encoding

Binary value being encoded	Transmitted pulse center frequency
0	The RF carrier of the pulse is shifted by $-f_{dev}$
1	The RF carrier of the pulse is shifted by $+f_{dev}$

The value of parameter f_{dev} is specified in 18.2.5.1.

18.2.5.1 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.

18.2.5.2 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 18-1 for the base mode and Figure 18-3 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 18-4a.

18.2.5.3 Dual-frequency modes synchronization

No additional synchronization measures are needed for dual-frequency modes since the PBFSK modulation ensures that pulses are transmitted in every symbol.

18.2.6 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 µs is divided into 128 equal duration slots, that is of 7.8125 ns. The 1 µs 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 µs, 0.5 µs, and 0.25 µs, respectively). The modified PRP are obtained by subtracting the time shift of $k_{\mathrm{PRP}} \times 7.8125$ ns from the nominal chipping periods, where k_{PRP} has values in the range of 0 to 7, as per Table 18-4b, where $T_{\mathrm{CHIP}} = T_{\mathrm{dsym}}$. The first row of Table 18-4b contains the nominal PRFs.

Table 18-4b—Variable PRP parameters for each nominal PRF

PRP Mode k_{PRP}	T_{CHIP} (µs)	PRF (MHz)	T_{CHIP} (µs)	PRF (MHz)	T_{CHIP} (µs)	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

The selection of k_{PRP} is achieved using the *phyLrpUwbPrp* attribute.

18.3 LRP UWB SHR

18.3.2 LRP UWB SHR preamble

18.3.2.1 LRP UWB base mode SHR preamble

Change 18.3.2.1 as follows:

The LRP UWB base mode SHR preamble consists of a continuous stream of pulses at the base mode PRF of 1 MHz, with <u>the number of pulses being</u> ~~a length~~ between 16 and 128<u> 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</u>.

Insert new subclause 18.3.2.4 after 18.3.2.3 as follows:

18.3.2.4 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 18-4a, and transmitted at the nominal PRF of 1 MHz, 2 MHz, or 4 MHz as specified in Table 18-1, or the PRF according to the specification in Table 18-4b when variable PRP is being employed. The number of pulses in the preamble shall be between 16 and 256.

18.3.3 LRP UWB SHR SFD

Insert a new subclause heading 18.3.3.1 to contain the existing text and figure from 18.3.3 as follows:

18.3.3.1 SFD for devices that are not LRP-ERDEV

Insert new subclause 18.3.3.2 after 18.3.3.1 (formerly the content of 18.3.3) as follows:

18.3.3.2 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 18-4c. 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 18-4c—SFD sequences for the LRP-ERDEV

SFD length	*phyLrpUwbSfdSelector* 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
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

18.5 LRP UWB PSDU

Insert a new subclause heading 18.5.1 to contain the existing text from 18.5 as follows:

18.5.1 General

Insert new text and new subclause 18.5.2 at the end of 18.5.1 (formerly the content of 18.5) as follows:

In non-EPC dual-frequency modes the PSDU is encoded as per 18.2.5.2, and in dual-frequency mode using EPC the PSDU is encoded as per 18.5.2.

18.5.2 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 $T_{\mathrm{PPM}} = (M - 1) \times d_{\mathrm{PPM}}$
— A guard interval of duration $T_{\mathrm{guard}} = T_{\mathrm{dsym}} - T_{\mathrm{PPM}}$

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 18-7. The time interval d_{PPM} is selected according to the modulation as specified in Table 18-8a. 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.

Table 18-8a—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
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

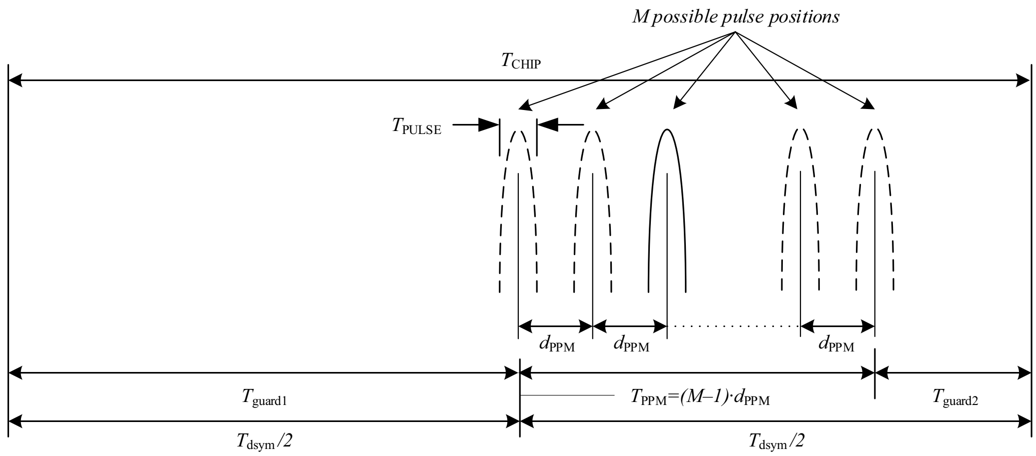

Figure 18-7—Dual-Frequency EPC mode symbol structure

When using EPC in conjunction with the variable PRP described in 18.2.6, the appropriate T_{dsym} is taken from Table 18-4b 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):

$$T_{\text{PPM}} = (M-1) \times d_{\text{PPM}} = 31 \times 7.8125 \text{ ns} = 242.1875 \text{ ns}$$

$$T_{\text{guard}} = T_{\text{dsym}|k_{\text{PRP}=7}} - T_{\text{PPM}} = 945.3125 \text{ ns} - 242.1875 \text{ ns} = 703.125 \text{ ns}$$

$$T_{\text{guard1}} = \frac{T_{\text{dsym}}}{2}$$

$$T_{\text{guard2}} = T_{\text{guard}} - T_{\text{guard1}}$$

18.6 LRP UWB location enhancing information postamble

Change the first dashed list in 18.6 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 18.3.2.4 for the SHR, the number of pulses being defined in the DataRequestRangingDescriptor

18.7 LRP UWB transmitter specification

18.7.1 Pulse shape

Insert new text and Figure 18-8 at the end of 18.7.1 as follows:

For dual-frequency modes using the PBFSK modulation, the normalized power spectral density (PSD) of the modulated frequency response shall comply with the Transmit PSD Mask specified in 18.7.3 for the chosen operating band. Normalized PSD means PSD being such that the largest measured bin value is subtracted from all measured bins. Figure 18-8 is an example of LRP-ERDEV dual frequency mode spectrum fitting into the PSD mask for channel band 6 (as specified in Table 18-10).

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 15-13. 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 ns ± 0.35 ns.

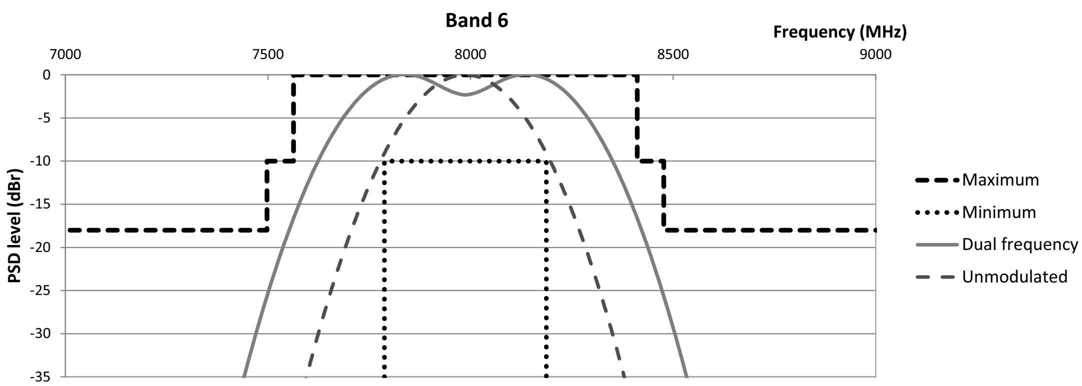

Figure 18-8—Example of PSD mask spectral compliance for dual-frequency modes

18.7.2 Pulse timing

Insert a new paragraph after the first paragraph of 18.7.2 as follows:

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.

18.7.3 Transmit PSD mask

Change the first sentence of 18.7.3 as follows:

The transmitter shall be capable of operating ~~operate~~ with a PSD ~~power spectral density~~ contained by at least one of four ~~three~~ PSD masks defined in Table 18-9 and shown in Figure 18-9. The LRP-ERDEV shall additionally be capable of supporting at least one of the channels listed in Table 18-10, where for each channel supported the transmitter shall be capable of operating with the respective PSD defined in Table 18-10 and Figure 18-10.

Change the heading row and insert a new row at the bottom of Table 18-9 as follows (unchanged rows not shown):

Table 18-9—LRP UWB PHY PSD mask

Channel ~~B~~band number	f_n (MHz)	Frequency (MHz)	PSD limit (dBr)
…			
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

Insert new Figure 18-9, Table 18-10, and Figure 18-10 at the end of 18.7.3 as follows:

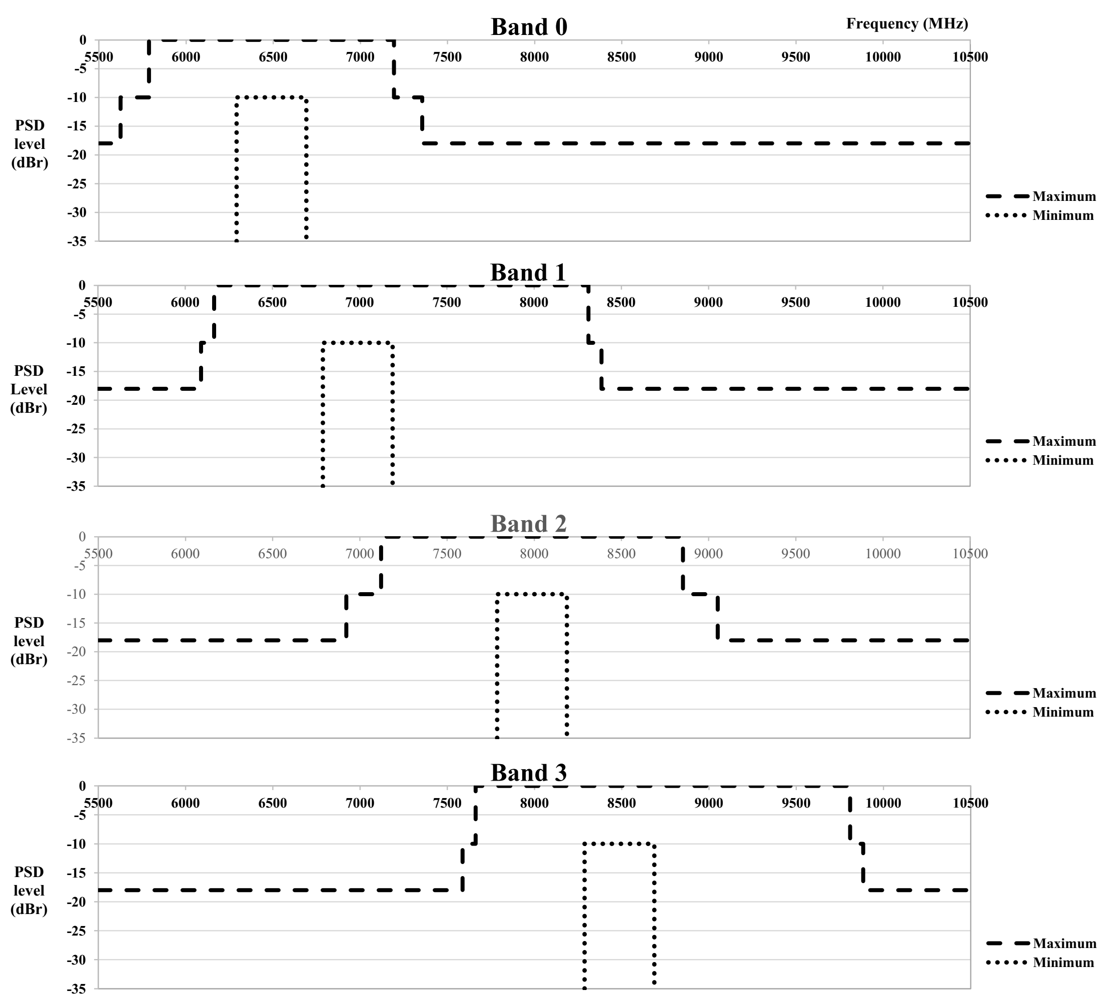

Figure 18-9—LRP-ERDEV LRP UWB PHY PSD masks

Table 18-10—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

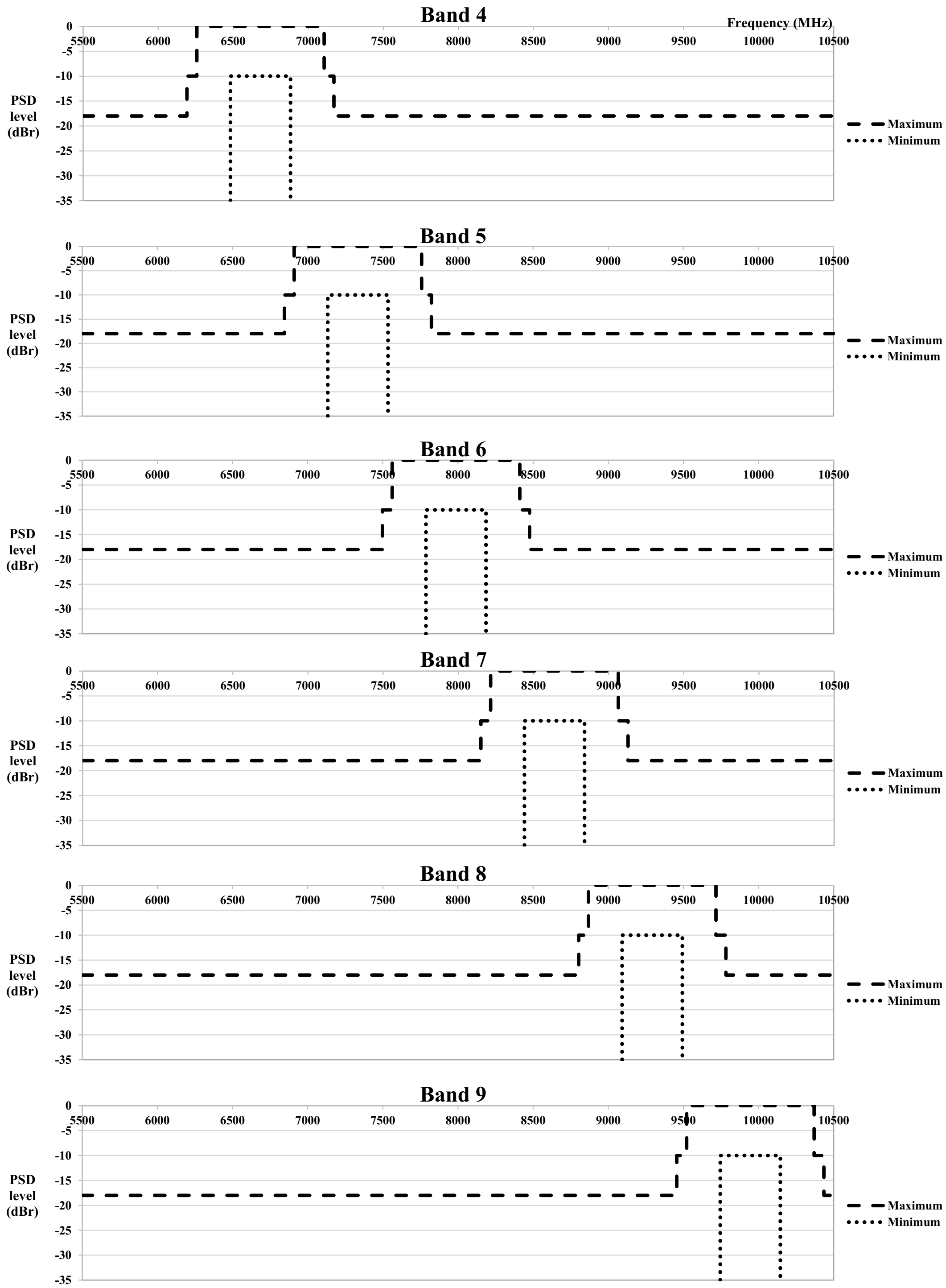

Figure 18-10—LRP-ERDEV channelized PSD masks

Delete the heading and text for 18.8 and insert new subclause 18.8 after 18.7 as follows:

18.8 LRP UWB transmit and receive timing requirements

18.8.1 Fixed reply time

The receive-to-transmit reply time for a device with a *phyFixedReplyTimeSupported* attribute value of TRUE shall be the fixed reply time as specified in Table 18-11 selected by the *phyLrpUwbFixedReplyTime* attribute. The RSTU units are specified in 6.9.1.5 and the pulse timing accuracy for the LRP-ERDEV is specified in 18.7.2.

Table 18-11—Fixed reply times for the LRP-ERDEV

Value of the *phyLrpUwbFixedReplyTime* attribute	Selected fixed reply time (RSTU, number of base chip periods)
FRT3	3
FRT7	7
FRT15	15
FRT31	31

Assuming nominally synchronized transmitter and receiver, a fixed reply time of FRTx corresponds to a equivalent time of FRT$x + 1$ between the active portion (pulses) of the last received chip and the first transmitted chip. In the example of Figure 18-11, a fixed reply time value of FRT3 defines a pulse-to-pulse fixed reply time of four RSTU.

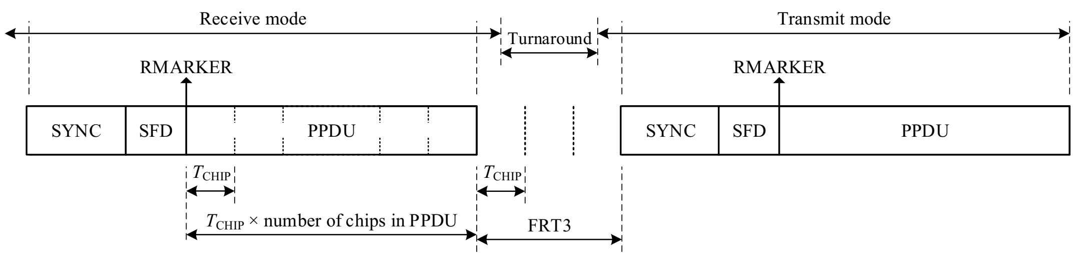

Figure 18-11—Fixed reply time as a function of FRT*x* parameter for LRP-ERDEV

18.8.2 Turnaround times

When the *phyFixedReplyTimeSupported* 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 18-11 selected by the *phyLrpUwbFixedReplyTime* attribute.

Annex A

(informative)

Bibliography

Insert the following reference before [B1]:

[Ba] "15.4z HRP UWB PHY Test Vectors," IEEE 802.15 document 15-20-0002-00-004z, 2020.[6]

Insert the following reference after [B6]:

[B6a] "Description 15.4z HRP UWB PHY Test Vectors," IEEE 802.15 document 15-20-0003-01-004z, 2020

Insert the following two references after [B7]:

[B7a] 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.[7]

[B7b] IETF RFC 3629, UTF-8, a transformation format of ISO 10646, Internet Engineering Task Force.[8]

Insert the following reference after [B20]:

[B20a] Srdjan Capkun, David Basin, Boris Danev, "Authenticated Ranging of IEEE 802.15.4," IEEE 802.15, document 15-19-0423, 2019.

[6]IEEE 802.15 documents are available at https://mentor.ieee.org/802.15/documents.
[7]IEEE publications are available from The Institute of Electrical and Electronics Engineers (https://standards.ieee.org/).
[8]IETF RFCs are available from the Internet Engineering Task Force (http://www.ietf.org/).

Annex D

(informative)

Protocol implementation conformance statement (PICS) proforma[9]

D.7 PICS proforma tables

D.7.3 Major capabilities for the PHY

D.7.3.5 Channel capabilities for LRP UWB PHY

Change Table D.5 as follows:

Table D.5—LRP UWB channels

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
PCH17	Channel Number 0	~~Table 10-13~~ Table 18-9	RF9: O.10			
PCH18	Channel Number 1	~~Table 10-13~~ Table 18-9	RF9: O.10			
PCH19	Channel Number 2	~~Table 10-13~~ Table 18-9	RF9: O.10			
PCH20	Channel Number 3	Table 18-10	RF9: O.10			
PCH21	Channel Number 4	Table 18-10	RF9: O.10			
PCH22	Channel Number 5	Table 18-10	RF9: O.10			
PCH23	Channel Number 6	Table 18-10	RF9: O.10			
PCH24	Channel Number 7	Table 18-10	RF9: O.10			
PCH25	Channel Number 8	Table 18-10	RF9: O.10			
PCH26	Channel Number 9	Table 18-10	RF9: O.10			

[9]Copyright release for PICS proformas: 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.

Insert new Annex H after Annex G as follows:

Annex H

(informative)

STS generation

H.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 key 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.

H.2 Test vectors for STS generation

This example specifies the first two blocks generated by the DRBG described in 15.2.9 using the following initialization:

STS key = 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 key = *phyHrpUwbStsKey*, and data = *phyHrpUwbStsVUpper96* || *phyHrpUwbStsVCounter*.

The associated value of the RSKD IE (as defined in 7.4.4.42) 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) = 0111101010100110111101100011111011111001000101111010111001000111
0001000101011110101101101111111000111011010110100101011110010001
0100000111011010000011000111010100000011010101100110001101010111
1110101111110011100010110010110000010010101110110011111010010010

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.

H.3 Resulting STS modulation

Bits C(0:255) from H.2 are mapped to BPSK modulation polarities of the first 256 pulses of the STS, as described in 15.2.9.2. Symbols A(*i*) are then spread by δ_L = 8 chips in BPRF mode, or δ_L = 4 chips in HPRF mode. The resulting symbols A(*i*) for the example data are:

A(0:255) = +−−−−+−+−+−++−−+−−−−+−−+++−−−−−+−−−−−++−+++−+−−−−+−+−−−++−+++−−−
+++−+++−+−+−−−−+−+−−+−−+−−−−−−−+++−−−+−−+−+−−+−++−+−+−−−−++−+++−
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