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IEEE Standard for
Local and metropolitan area networks—

Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)

Amendment 5: Physical Layer Specifications for Low Energy, Critical Infrastructure Monitoring Networks

IEEE Computer Society

Sponsored by the
LAN/MAN Standards Committee

IEEE
3 Park Avenue
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USA

IEEE Std 802.15.4k™-2013
(Amendment to
IEEE Std 802.15.4™-2011
as amended by IEEE Std 802.15.4e™-2012,
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Approved 14 June 2013

IEEE-SA Standards Board

Abstract: Two PHYs (DSSS and FSK) that support critical infrastructure monitoring applications are provided in this amendment to IEEE Std 802.15.4™-2011. In addition, only those MAC modifications needed to support the implementation of the two PHYs are described in this amendment.

Keywords: IEEE 802.15.4™, IEEE 802.15.4k™, low data rate, low power, LR-WPAN, PAN, personal area network, radio frequency, RF, wireless personal area network, WPAN

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Introduction

This introduction is not part of IEEE Std 802.15.4k-2013, IEEE Standard for Local and metropolitan area networks—Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)—Amendment 5: Physical Layer Specifications for Low Energy, Critical Infrastructure Monitoring Networks.

This amendment specifies alternate PHYs in addition to those of IEEE Std 802.15.4-2011. In addition to the new PHYs, the amendment also defines those MAC modifications needed to support their implementation.

Contents

IEEE Standard for
Local and metropolitan area networks—

Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)

Amendment 5: Physical Layer Specifications for Low Energy, Critical Infrastructure Monitoring Networks

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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.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

Insert the following definitions alphabetically into 3.1:

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

3.2 Acronyms and abbreviations

Insert the following acronyms alphabetically into 3.2:

CDMA	code division multiple access
CIC	central inventory control
CLON	co-located orthogonal network
FVS	fragment validation sequence
I-ACK	fragment incremental acknowledgment
I-RIT	implicit receiver initiated transmission
LECIM	low energy, critical infrastructure monitoring
OVSF	orthogonal variable spreading factor
PCA	priority channel access
P-FSK	position-based frequency shift keying
P-GFSK	position-based Gaussian frequency shift keying
RIV	remainder initialization value
RZ Time	rendezvous time
SF	spreading factor
TID	transaction identifier
TRLE	time-slot relaying based link extension

4. General description

4.3 Network topologies

4.3.1 Star network formation

Insert the following paragraph at the end of 4.3.1:

Low energy critical infrastructure monitoring (LECIM) networks primarily operate in a star topology. LECIM networks are typically asymmetric in energy supply and capability, having a PAN coordinator that is mains powered (or otherwise provided a substantial power source) and energy and/or cost constrained devices. The PAN coordinator typically monitors the channel more often than a device. A device sleeps unless it has a data frame to send.

4.5 Functional overview

4.5.1 Superframe structure

4.5.1.1 General

Insert the following item at the end of the list in 4.5.1.1:

— Support for priority channel access (PCA) in the contention access period (CAP) of the superframe structure, as described in 5.1.1.4.5 and 5.1.1.4a

4.5.4 Improving probability of successful delivery

Insert the following new subclause (4.5.4.1a) after 4.5.4.1:

4.5.4.1a CSMA-CA used with PCA

When a critical event occurs in a nonbeacon-enabled PAN, PCA is achieved by use of the PCA backoff algorithm described in 5.1.1.4.5. The PCA backoff algorithm, on average, provides a shorter backoff duration for PCA than for normal access. In addition, the PCA conducts a clear channel assessment (CCA) at regular intervals, even if it is assessed to be busy, in order to gain immediate access to the channel once it is assessed to be idle.

When a critical event occurs in a beacon-enabled PAN, fixed-size CAP time allocations are dedicated in a superframe for PCA. Priority frame transmission may commence in the priority allocations and continue through the duration of the CAP. Priority frames access the channel using the PCA backoff algorithm.

4.5.4.2 ALOHA mechanism

Insert following paragraph after the last paragraph of 4.5.4.2:

When using slotted ALOHA with PCA (5.1.1.4a), PCA allocations of more than four consecutive backoff slot durations are introduced in the CAP of the superframe. The first such allocation dedicated for PCA traffic occurs immediately after the beacon. The backoff slot length is PHY dependent and accommodates, at minimum, the transmission of a single MAC protocol data unit (MPDU) fragment.

Insert the following new subclause after 4.5.4.2:

4.5.4.2a MPDU fragmentation

MPDU fragmentation operates on the MHR and MSDU portions of the MPDU and adapts the MAC frame structure to the specific PHY and PHY operating mode. To reduce over-the-air overhead, MAC header information is compressed or suppressed in the over-the-air exchange, by establishing a fragment sequence (transaction) context. The combination of the information in the fragment and the fragment sequence context provides identification of the individual fragment, the sequence to which it belongs, and where the fragment fits into the sequence. Each fragment carries an incremental validity check sequence for detecting errors; therefore, the MFR is not transmitted. Each fragment is validated and, when all valid fragments are received, the MPDU is reconstructed. A schematic view of the fragmentation process is shown in Figure 6a.

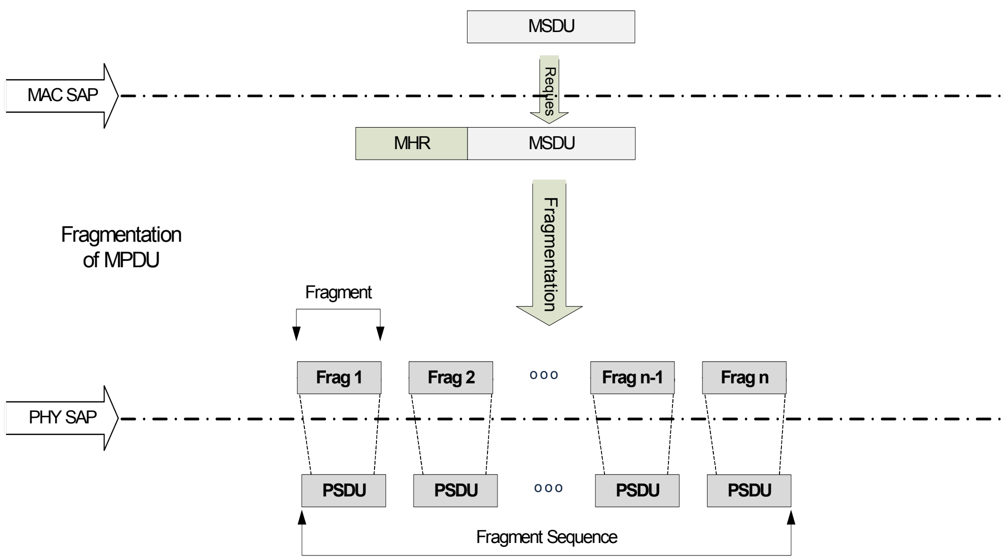


Figure 6a—Schematic view of MPDU fragmentation

Each fragment is individually acknowledged and retransmitted, if required. Retransmission of only the missed fragments reduces air time and improves reliability.

4.5.4.3 Frame acknowledgment

Insert the following new subclause (4.5.4.3a) after 4.5.4.3:

4.5.4.3a Fragment incremental acknowledgment (I-ACK)

The I-ACK is used during the fragment sequence transfer to determine which fragments have been received successfully and which fragments need to be retransmitted. An I-ACK includes the status of one or more fragments. The format of the I-ACK is given in 5.4.2.1.2.

4.5.4.4 Data verification

Insert the following paragraph at the end of 4.5.4.4:

To accommodate individual fragment acknowledgements, a fragment validation sequence (FVS) is included with each fragment. The recipient uses the FVS and fragment number to determine which fragments of the sequence have been received correctly and which are missing. The FVS is described in 5.4.1.2.

5. MAC protocol

5.1 MAC functional description

5.1.1 Channel access

5.1.1.4 CSMA-CA algorithm

Insert the following new subclause (5.1.1.4.5) after 5.1.1.4.4:

5.1.1.4.5 CSMA-CA with PCA

An MSDU or MSDU fragment in which the CriticalEventMessage parameter in the MCPS-DATA.request primitive is TRUE is referred to as a critical event message. The CSMA-CA with PCA backoff algorithm is used before the transmission of a critical event message during the CAP.

In a beacon-enabled PAN when PCA is enabled (*macPriorityChannelAccess* is true), the LECIM PCA Allocation Specification payload IE shall be included in enhanced beacon frames that are sent at every beacon interval.

In a beacon-enabled PAN, the MAC sublayer employs the slotted version of the CSMA-CA with PCA backoff algorithm, as shown in Figure 11c, for transmissions in the CAP of the superframe. Conversely, in a nonbeacon-enabled PAN or if a beacon could not be located in a beacon-enabled PAN, the MAC sublayer may transmit using the unslotted version of the CSMA-CA with PCA backoff algorithm, as shown in Figure 11d.

The variable *NB* is not used in CSMA-CA with PCA backoff algorithm. The PCA backoff algorithm is used during the transmission of a priority message: the backoff exponent *BE* is initialized to the value of $macMinBE - 1$ or 1, whichever is larger, prior to the first transmission attempt, and *BE* remains constant for subsequent retransmissions. The MAC sublayer is responsible for maintaining a variable called *Total backoffs* (*TB*), which indicates the number of remaining backoff periods since the start of the CSMA-CA with PCA backoff algorithm. *TB* is initialized to a random value between 0 and $2^{BE} - 1$. The PCA backoff algorithm follows a persistent CSMA mechanism, meaning that the device continues to monitor the channel and decrements *TB* by one any time the channel is sensed idle in a backoff period, in order to gain access to the channel in a timely manner. The slotted PCA backoff algorithm is illustrated in Figure 11c and the unslotted PCA backoff algorithm is illustrated in Figure 11d within the dashed line rectangles, respectively.

In the slotted CSMA-CA with a PCA backoff algorithm, the MAC sublayer shall ensure that, after the persistent random backoff, the remaining CSMA-CA operations can be undertaken and the entire transaction can be transmitted before the end of the CAP. If *TB* is greater than the remaining number of backoff periods in the CAP, the MAC sublayer pauses the *TB* countdown at the end of the CAP and resumes it at the start of the CAP in the next superframe. If *TB* is less than or equal to the remaining number of backoff periods in the CAP, the MAC sublayer applies the PCA backoff algorithm one CCA attempt further and then again evaluates whether there is sufficient time to proceed. The MAC sublayer may proceed if the remaining CSMA-CA algorithm steps, the frame transmission, and any acknowledgment can be completed before the end of the CAP. If there is not sufficient time to proceed, the MAC sublayer waits until the start of the CAP in the next superframe before continuing to apply the PCA backoff algorithm.

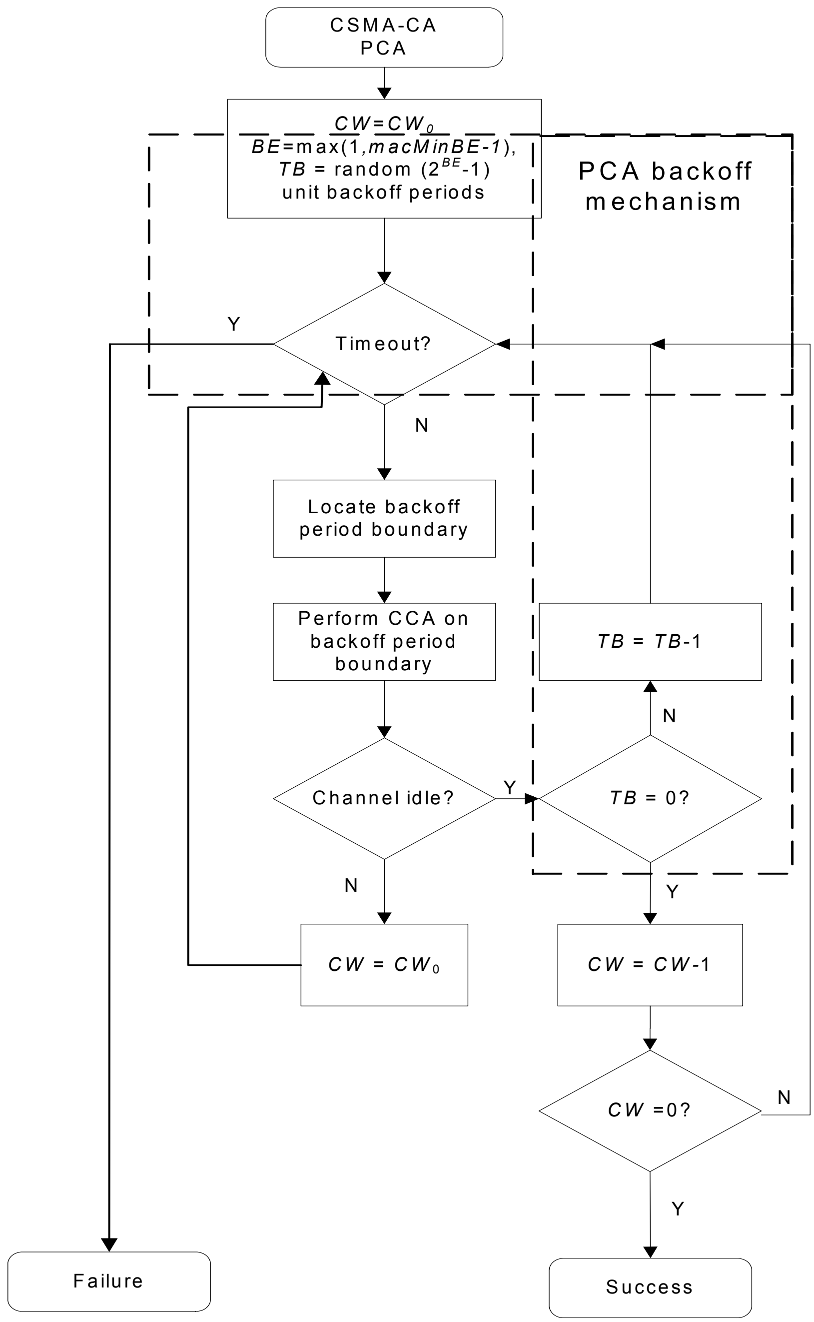


Figure 11c—Algorithm for slotted CSMA-CA with PCA

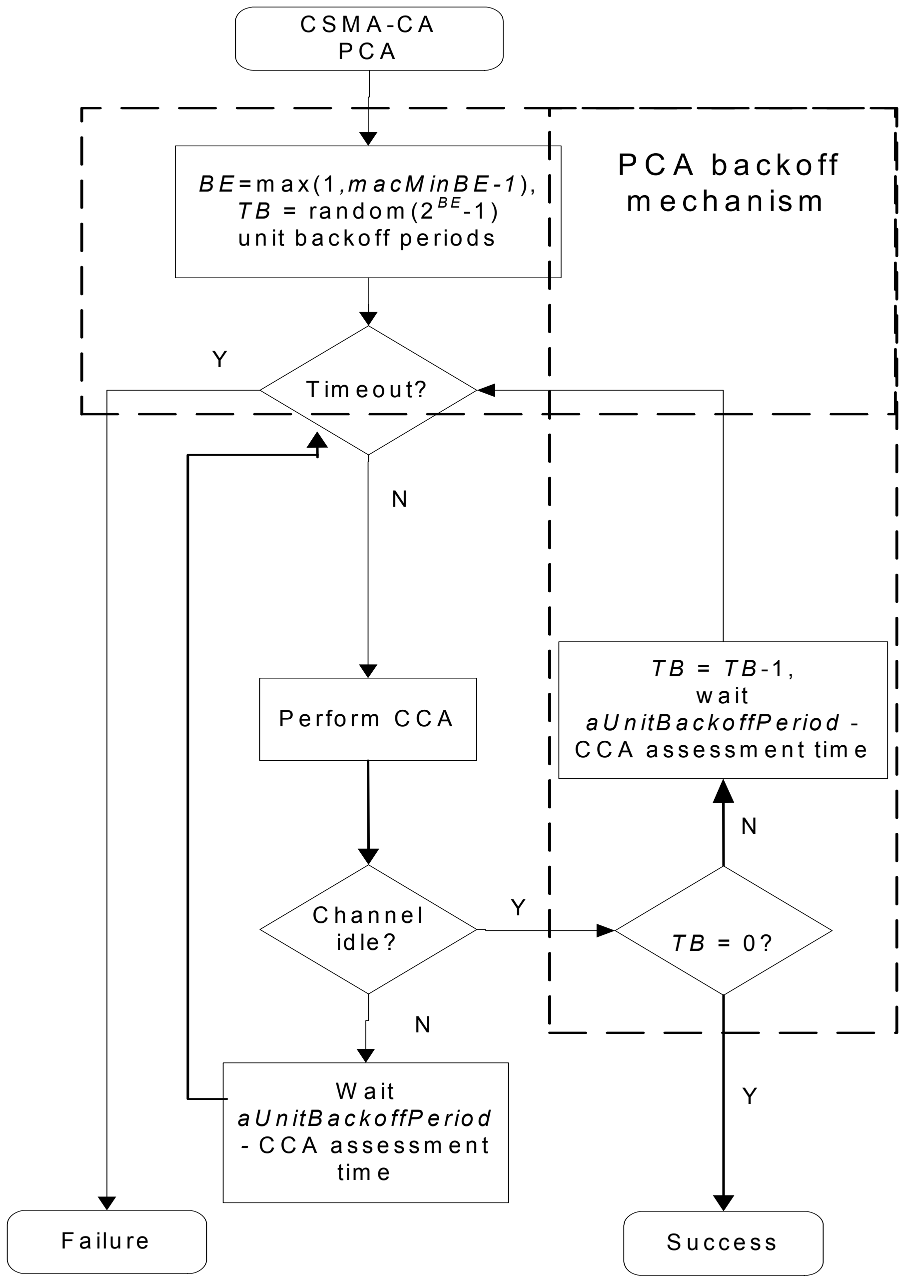


Figure 11d—Algorithm for unslotted CSMA-CA with PCA

When operating a LECIM PHY in a nonbeacon-enabled PAN using unslotted CSMA-CA, the critical event message transmission may be initiated at any time, and the PCA backoff algorithm follows Figure 11d.

In a beacon-enabled PAN, the length of a PCA allocation shall be at least 880 symbol durations. When *macPriorityChannelAccess* is TRUE, the minimum number of PCA allocations in a superframe is defined by the MAC personal area network information base (PIB) attributes *macPCAAllocationSuperRate*, *macPCAAllocationRate*, and *macCritMsgDelayTol*. The relations of the parameters are illustrated in Table 0.0a.

Table 0.0a—PCA MAC PIB attribute relations

Value of *macPCAAllocationSuperRate*	Superframe duration (SD)	*macPCAAllocationRate*
FALSE	$SD \le \frac{macCritMsgDelayTol}{3}$	Maximum value $\left\lfloor \frac{macCritMsgDelayTol}{3 \times SD} \right\rfloor$
TRUE	$\frac{macCritMsgDelayTol}{3} < SD \le macCritMsgDelayTol$	Minimum value 1
TRUE	$SD > macCritMsgDelayTol$	Minimum value $\left\lceil \frac{SD}{macCritMsgDelayTol} \right\rceil$

In Table 0.0a, $\lfloor \ \rfloor$ indicates the closest integer less than or equal to its argument and $\lceil \ \rceil$ indicates the closest integer larger than or equal to its argument. When *macPCAAllocationSuperRate* is FALSE, *macPCAAllocationRate* is interpreted as a subrate, and it indicates the maximum number of consecutive superframes for which only one PCA allocation is required. In this case, the PCA allocations need only occur within the superframes having *macBSN* that are integer divisible by the *macPCAAllocationRate* value. When $SD \le macCritMsgDelayTol/3$, *macPCAAllocationSuperRate* shall be set to FALSE; otherwise, it shall be set to TRUE. When *macPCAAllocationSuperRate* is TRUE*, macPCAAllocationRate* indicates the minimum number of PCA allocations required per superframe.

If there are multiple PCA allocations per superframe, the first allocation occurs at the start of the CAP. The remaining PCA allocations are distributed throughout the superframe, but no PCA allocation shall occur outside the CAP.

When a critical event message transmission is initiated within the CAP during a time that is not a PCA allocation, CSMA-CA, as defined in 5.1.1.4, with the previously described PCA backoff algorithm may be used.

If DSME is utilized with *macCAPReductionFlag* set to TRUE and the multi-superframe duration (MD) is longer than *macCritMsgDelayTol*, then *macPriorityChannelAccess* shall be set to FALSE.

When *macPriorityChannelAccess* is TRUE, a PCA allocation shall not occur if the CAP length duration is less than *aMinCAPLength* plus the time required for a single PCA allocation.

5.1.1.4a LECIM ALOHA PCA

When PCA is in use with CCA Mode 4 (ALOHA), PCA is achieved using a modified version of the PCA backoff algorithm described in 5.1.1.4.5. Instead of one backoff period being equal to *aUnitBackoffPeriod*, a backoff period is defined as *macLECIMAlohaUnitBackoffPeriod*.

When MPDU fragmentation is in use, the value of *macLECIMAlohaUnitBackoffPeriod* should be long enough to accommodate the transmission of a single MPDU fragment with the associated interframe spacing (IFS) period and an I-ACK frame. When MPDU fragmentation is not in use, the value of *macLECIMAlohaUnitBackoffPeriod* should be long enough to accommodate the transmission of a maximum-sized MPDU with the associated IFS and an ACK frame.

When CCA Mode 4 (ALOHA) with the PCA backoff algorithm is used in a beacon-enabled PAN, the process illustrated in Figure 11c is modified as follows: *CW* is initialized to 1. The algorithm advances directly from the state “Locate backoff period boundary” to the state “TB = 0?”

When CCA Mode 4 (ALOHA) with the PCA backoff algorithm is used in a nonbeacon-enabled PAN, the process illustrated in Figure 11d is modified as follows: when the state “Timeout?” returns “N,” the algorithm advances directly to the state “TB = 0?”

When *macPriorityChannelAccess* is set as TRUE, each PCA allocation shall be at least four consecutive *macLECIMAlohaUnitBackoffPeriod* in duration. The first PCA allocation shall begin at the start of the CAP. The number of PCA allocations per superframe is described by Table 0.0a.

A PCA allocation cannot occur if the CAP length duration is less than *aMinCAPLength* plus the time required for a single PCA.

5.1.6 Transmission, reception, and acknowledgment

Insert the following sentence at the end of the first paragraph:

Additional processing is performed when MPDU fragmentation is in use, as described in 5.4.

5.1.6.1 Transmission

Change the sixth paragraph in 5.1.6.1:

If the frame is to be transmitted on a beacon-enabled PAN, the transmitting device shall attempt to find the beacon before transmitting. If the beacon is not being tracked, as described in 5.1.1.4, and hence the device does not know where the beacon will appear, it shall enable its receiver and search for at most [*aBaseSuperframeDuration* $\times (2^n + 1)$], where n is the value of *macBeaconOrder*, in order to find the beacon. If the beacon is not found after this time, the device shall transmit the frame following the successful application of the unslotted version of the CSMA-CA algorithm, as described in 5.1.1.4. Once the beacon has been found, either after a search or due to its being tracked, the frame shall be transmitted in the appropriate portion of the superframe. Transmissions in the CAP shall follow a successful application of the slotted version of the CSMA-CA algorithm, as described in 5.1.1.4, and transmissions in a GTS shall not use CSMA-CA. <u>When the LECIM DSSS PHY is in use in a beacon-enabled PAN, transmissions after the beacon shall commence *phyLECIMDSSSPPDUTxAt* following the reception of the last symbol of the beacon frame.</u>

5.1.6.2 Reception and rejection

Insert the following new paragraph before the first paragraph of 5.1.6.2:

When MPDU fragmentation is in use, see 5.4.2.1 for a description of fragment acknowledgement.

5.1.6.4 Use of acknowledgments and retransmissions

5.1.6.4.2 Acknowledgment

Change the second paragraph of 5.1.6.4.2 as indicated:

The transmission of an acknowledgment frame in a nonbeacon-enabled PAN or in the CFP shall commence t_{ack} ~~*macSIFSPeriod*~~ after the reception of the last symbol of the data or MAC command frame. The transmission of an acknowledgment frame in the CAP shall commence either t_{ack} ~~*macSIFSPeriod*~~ after the reception of the last symbol of the data or MAC command frame or at a backoff period boundary. In the latter case, the transmission of an acknowledgment frame shall commence between t_{ack} ~~*macSIFSPeriod*~~ and (t_{ack} ~~*macSIFSPeriod*~~ + *aUnitBackoffPeriod*) after the reception of the last symbol of the data or MAC command frame. The value of t_{ack} is 1 ms for the SUN PHYs and LECIM PHYs. The value of t_{ack} is equal to *macSIFSPeriod* for all other PHYs.

5.1.8 Ranging

5.1.8.4 The ranging exchange

Insert the following new subclauses (5.1.8a-5.1.8a.2) after 5.1.8.4:

5.1.8a PHY parameter change notification procedure

This procedure is initiated through the MLME-PHY-OP-SWITCH.request primitive, as described in 6.2.22.1, in order to notify one or more peer devices of the intention to switch operating band, channel, or other PHY-specific operating parameters.

5.1.8a.1 Signaling using beacon frames

This method is initiated by the reception of the MLME-PHY-OP-SWITCH.request primitive with the SignalMethod parameter value set to USE_BEACON. The method requires that the enhanced beacon feature is supported and that the device is the PAN coordinator using enhanced beacon frames. If these conditions are not met, the device shall respond with the MLME-PHY-OP-SWITCH.confirm primitive having the appropriate status parameter value indicating the reason for the request failure.

A PHY Parameter Change IE, as defined in 5.2.4.23, shall be generated and inserted in the next outgoing enhanced beacon frame. The Effective Time of Change field of the IE shall be set to the value of the TargetTime parameter of the MLME-PHY-OP-SWITCH.request primitive. The Notification Time field shall be updated with the local time of the device each time it is transmitted. An Operating Mode Description IE (5.2.4.29) shall be generated according to the values in the PHYParameterList and inserted in the same enhanced beacon frame following the PHY Parameter Change IE.

If the value of the RepeatCount parameter of the MLME-PHY-OP-SWITCH.request primitive is nonzero, then the generated IEs shall be included in each enhanced beacon frame subsequently generated until the repeat count is exhausted or until the value in the TargetTime parameter has elapsed. If the RepeatCount parameter is zero, the generated IEs shall be included in only the next enhanced beacon frame.

5.1.8a.2 Signaling using multipurpose frames

This method is initiated by the reception of the MLME-PHY-OP-SWITCH.request primitive with the SignalMethod parameter value set to USE_MP. The method requires that the multipurpose frame (5.2.2.6) is supported. If this condition is not met, the device shall respond with the MLME-PHY-OP-SWITCH.confirm primitive having the appropriate status parameter value.

The device shall generate a PHY Op Mode Switch frame, which is a multipurpose frame containing a PHY Parameter Change IE and an Operating Mode Description IE. The addressing fields shall be set according to the DeviceAddrMode and DeviceAddr parameter values in the MLME-PHY-OP-SWITCH.request primitive. If the DeviceAddress parameter contains the broadcast address, then only the PAN ID addressing field shall be included, and it shall be set to the broadcast PAN ID. The PHY Parameter Change IE and an Operating Mode Description IE shall be generated using the TargetTime, RepeatCount, and PHYParameterList parameters, as described in 5.1.8a.1.

For a directed PHY Op Mode Switch frame, the frame shall be generated with the acknowledgment request (AR) field in the MHR set to request an acknowledgment and transmitted according to 5.1.6.

If the RepeatCount parameter value is greater than zero, the MLME shall repeat transmission of the frame after a delay equal to the value of the RepeatInterval parameter until the RepeatCount parameter value is exhausted. The Notification Time field shall be updated with the local time of the device each time it is transmitted.

When the TxIndirect parameter is set to TRUE, the PHY Op Mode Switch frame shall be sent using indirect transmission, as described in 5.1.5.

5.1.10 Deterministic and synchronous multi-channel extension (DSME)

5.1.10.1 DSME multi-superframe structure

Insert the following new paragraphs and Figure 34ga after the last paragraph of 5.1.10.1:

When *macExtendedDSMEenabled* is TRUE, the Extended DSME PAN Descriptor IE shall be included in enhanced beacon frames that are sent every beacon interval in an Extended DSME-enabled PAN.

When *macExtendedDSMEenabled* is TRUE, the values of the multi-superframe order, MO, the superframe order, SO, and the beacon order, BO, are related as follows:

$$SO \le MO \le [BO+\mathrm{len}(BSN)]$$

where

len(BSN) is 8 when the enhanced beacon frame contains the Sequence Number field and 0 when the Sequence Number field is not present.

Because the value of MO can be larger than that of BO, there may be multiple beacon intervals BIs within an MD. An example of a multi-superframe structure with the value of MO larger than that of BO is shown in Figure 34ga.

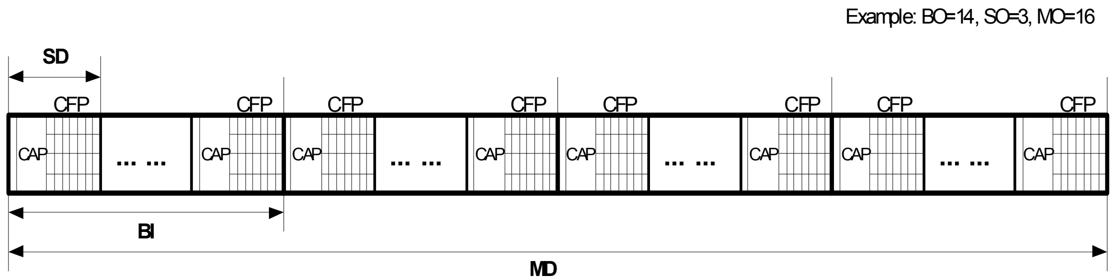


Figure 34ga—Example of DSME multi-superframe structure (MO>BO)

5.1.10.5 DSME-GTS allocation and management

5.1.10.5.1 DSME-GTS allocation

Insert the following paragraph at the end of 5.1.10.5.1:

Devices in a DSME-enabled PAN may be allocated DSME-GTSs during the association procedure. If *macExtendedDSMEenabled* is TRUE and a device is instructed to associate with the PAN through the MLME-ASSOCIATE.request primitive having the DSMEAssociationType parameter set to one, the device requests DSME-GTS allocation by sending a DSME-Association request command to a coordinator with the Extended DSME-GTS Allocation field present, as described in 5.3.11.2.5. On receipt of the DSME-Association request command, the MAC sublayer of the coordinator informs the next higher layer that DSME-GTS allocation is being requested through the MLME-ASSOCIATE.indication primitive with the DSMEAssociationType parameter set to one. The next higher layer of the coordinator instructs the MAC sublayer to reply to the request for DSME-GTS allocation through the MLME-ASSOCIATE.response primitive. Then, the MAC sublayer of the coordinator sends a DSME-Association response command to the device containing the DSME-GTS allocation information described in 5.3.11.3. On receipt of the DSME-Association response command, the MAC sublayer of the device allocates a DSME-GTS and reports the results to the next higher layer.

5.1.10.5.3 DSME-GTS expiration

Insert the following two rows at the end of Table 1a:

Table 1a—Allocation counter table (*macDSMEACT*) description

Attribute	Type	Range	Description
Allocation Order	Integer	0x00–0x08	As defined in 5.3.11.3.6. If MO ≤ BO , the value of *macAllocationOrder* shall be set to zero.
BI Index	Integer	0x00–0xff	As defined in 5.3.11.3.7.

5.1.11 LE-transmission, reception, and acknowledgment

Insert the following new subclause (5.1.11.0) before 5.1.11.1:

5.1.11.0 LE transmission, reception, and acknowledgment with positive handshake

When *macLEHSenabled* is set to TRUE in the coordinator and the device, the data transmission, reception, and acknowledgment process illustrated in Figure 34na shall be used.

If the device received an acknowledgment frame from the coordinator indicating that the coordinator has a pending frame, the device shall send a data request command to the coordinator and wait for the corresponding data frame from the coordinator.

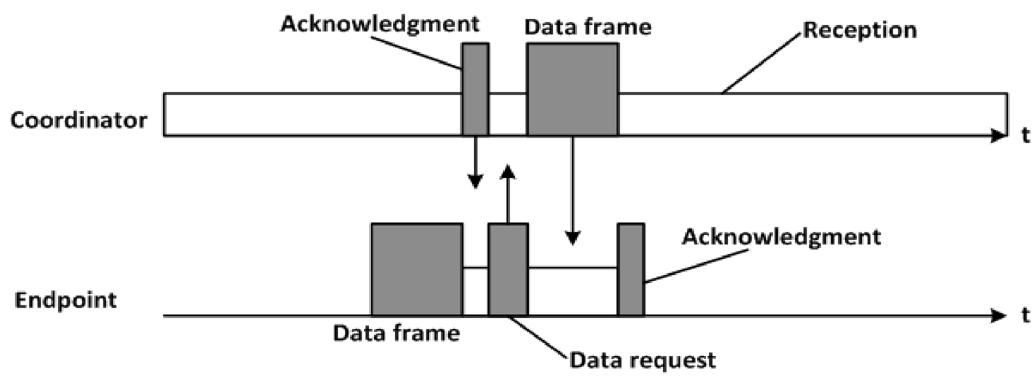


Figure 34na—LE transmission with positive handshake

If the acknowledgment is not received as expected, retransmission shall be performed as defined in 5.1.6.4.3. If, after sending the acknowledgment with the Frame Pending field set, the Data Request command is not received, the coordinator waits for a retransmission and, if received, repeats the acknowledgment with the Frame Pending field set.

5.1.11.1.2 CSL idle listening

Change 5.1.11.1.2 as indicated:

During idle listening, the CSL coordinator performs a channel sample every *macCSLPeriod* time. If no energy is detected on the channel~~the channel sample does not detect energy on the channel~~, the CSL coordinator disables the receiver until the next channel sample time~~,~~ and then performs the next channel sample. If the channel sample ~~receives~~ contains a wake-up frame, the CSL coordinator checks the destination address in the wake-up frame. Acknowledgment and ~~R~~retransmission~~s~~ ~~follow the same process~~ are performed as ~~defined~~ described in 5.1.6.4.3, with the additional requirement ~~except~~ that for each transmission~~,~~ ~~follows~~ the process ~~above~~described in this subclause is used. If ~~it~~ the destination address of the wakeup frame matches *macShortAddress*, the CSL coordinator checks whether the wake-up frame contains the Wake-up Interval field. If the wake-up frame does not contain the Wake-up Interval field, the CSL coordinator disables the receiver until the Rendezvous Time (RZ Time) in the wake-up frame and then enables the receiver to receive the payload data frame. ~~Otherwise,~~ If the wake-up frame does contain the Wake-up Interval field, and its value is nonzero, the CSL coordinator disables the receiver and transmits the data request frame with the AR field in the payload data frame set to one. Then the CSL coordinator waits for up to *macEnhAckWaitDuration*, as defined in Table 52j, for the enhanced acknowledgment frame. If the enhanced acknowledgment frame is received, the RZ Time is updated using the contents of the enhanced acknowledgment frame, and the receiver remains on for up to *macMaxFrameTotalWaitTime*, in order to receive the payload data frame.

When the wake-up frame contains the Wake-up Interval field with a nonzero value, the transmission, reception, and acknowledgment operation is as illustrated in Figure 34oa.

If the destination address of the wake-up frame does not match *macShortAddress*, the CSL coordinator disables the receiver until RZ Time plus the transmission time of the maximum length payload frame and the secure acknowledgment frame, and then resumes channel sampling.

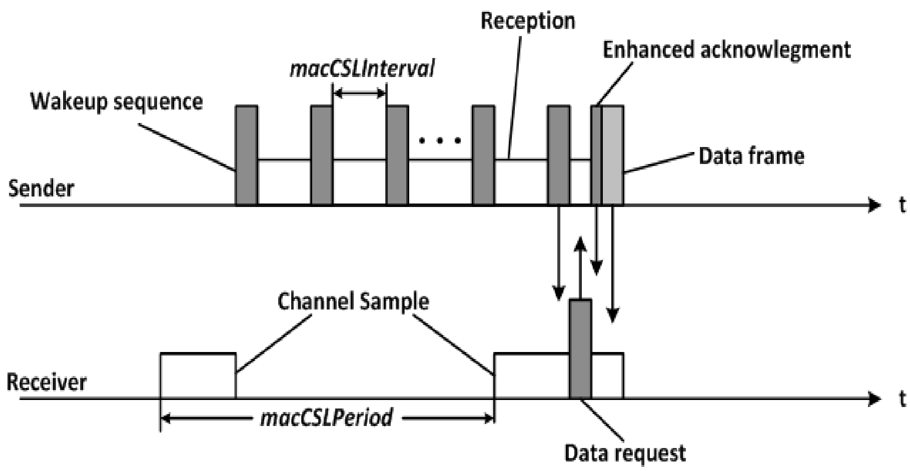


Figure 34oa—CSL operations when the wake-up frame interval is nonzero

5.1.11.1.3 CSL transmission

Change the first paragraph of 5.1.11.1.3 as indicated:

Each CSL transmission of a payload frame is preceded with a sequence of ~~back-to-back~~ wake-up frames (wake-up sequence).

5.1.11.1.4 Unicast transmission

Change 5.1.11.1.4 as indicated:

In unicast transmissions, the wake-up sequence length ~~can~~ may be long or short based on the following two cases:

Unsynchronized transmission: This is the case when the MAC sublayer does not know the CSL phase and period of the destination device. In this case, the maximum wake-up sequence length is *macCSLMaxPeriod*.

Synchronized transmission: This is the case when the MAC sublayer knows the CSL phase and period of the destination device. In this case, the wake-up sequence length is only the guard time against clock drift based on the last time when CSL phase and period updated about the destination device.

If the next higher layer has multiple frames to transmit to the same destination, it ~~can~~ may set the Frame Pending field in the Frame Control field ~~frame pending bit~~ to one in all but the last frame, in order to maximize the throughput.

CSL unicast transmission is performed in the following steps by the MAC sublayer:

a) Perform CSMA-CA to acquire the channel.

b) If the previous acknowledged payload frame to the destination has the ~~f~~Frame ~~p~~Pending ~~bit~~field set and is within *macCSLFramePendingWaitT* (defined in Table 52j), go to ~~step e)~~Step e.

c) If it is a synchronized transmission, wait until the destination device's next channel sample.

d) For the duration of wake-up sequence length (short or long)

   1) Construct wake-up frame with the destination short address and remaining time to payload frame transmission (at the end of wake-up sequence).

   2) Transmit wake-up frame.

   3) If *macCSLInterval* is not equal to zero, wait for up to *macCSLInterval* for the data request frame from the corresponding destination device. If the data request frame is received, then stop the transmission of the wake-up sequence, perform a CSMA-CA to acquire the channel, and transmit an enhanced acknowledgment frame with the RZ Time updated to zero.

e) Transmit payload frame.

f) Wait for up to *macEnhAckWaitDuration* (defined in Table 52j) ~~symbol time~~ for the enhanced acknowledgment frame if the ~~Acknowledge Request~~ AR field in the payload frame is set to one.

g) If the enhanced acknowledgment frame is received, update CSL phase and period information about the destination device from the Acknowledgment CSL Sync field.

h) If the enhanced acknowledgment frame is not received, start retransmission process.

Retransmissions follow the same process as defined in 5.1.6.4.3 except that each transmission follows the process above.

5.1.11.1.5 Broadcast transmission

Change the first paragraph of 5.1.11.1.5 as indicated:

Broadcast transmission is the same as unicast transmission except for the following conditions:

— It is always unsynchronized transmission.

— The destination address ~~in~~of the wake-up frames is set to 0xffff.

— If *macCSLInterval* is nonzero, the CSL coordinator will stop sending the wake-up sequence only after either receiving data request frames from all of the destination devices or when the *macCSLMaxPeriod* expires.

— Optionally includes LE CSL IE.

Insert the following new subclause (5.1.11.3) after 5.1.11.2.4:

5.1.11.3 Implicit receiver initiated transmission (I-RIT)

I-RIT is a low energy mode for nonbeacon-enabled PANs. I-RIT is designed to be used by end devices, such as sensors, that primarily transmit information to a coordinator but have no way of determining when they should make use of conventional RIT.

In order to enable I-RIT in an end device, the PIB attribute *macIRITEnabled* is set to TRUE. When an end device has I-RIT enabled, the device shall enable its receiver *macIRITOffsetInterval* after the last bit of its transmitted frame for a period of *macIRITListenDuration*, in order to allow the receipt of a frame from the coordinator. The values of *macCSLPeriod* and *macIRITOffsetInterval* shall be ignored when *macIRITenabled* is TRUE. Transmission and reception in I-RIT mode is illustrated in Figure 34sb.

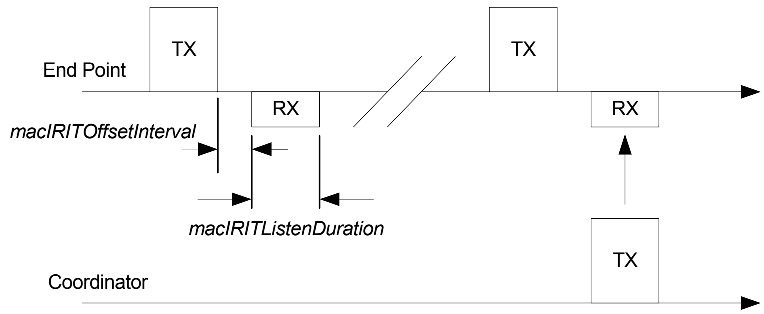


Figure 34sb—I-RIT transmission

5.2 MAC frame formats

5.2.1 General MAC frame format

5.2.1.1 Frame Control field

5.2.1.1.1 Frame Type field

Change the first paragraph of 5.2.1.1.1 and Table 2 as indicated:

The Frame Type field shall be set as defined in Table 2. If the Frame Type value indicates a fragment (i.e., 110), then the frame format shall not be as illustrated in Figure 35 but shall instead be as defined in 5.4.1.2.

5.2.1.1.3 Frame Pending field

Change the fourth paragraph of 5.2.1.1.3 as indicated:

When operating in low-energy (LE) CSL mode, the frame pending bit may be set to one to indicate that the transmitting device has ~~back-to-back~~pending frames to send to the same recipient and expects the recipient to keep the radio on until the frame pending bit is reset to zero.

Table 2—Values of the Frame Type field

Frame Type value	Description
000	Beacon
001	Data
010	Acknowledgment
011	MAC command
100	LLDN
101	Multipurpose
110	Fragment
~~110~~–111	Reserved

5.2.2 Format of individual frame types

5.2.2.1 Beacon frame format

5.2.2.1.1a Information Elements field

Insert the following new row at the end of Table 3b, and update the column heading as indicated:

Table 3b—EBR IEs per enabled attribute

Attribute ~~R~~request ~~I~~identifier	PIB attribute	IE type	IEs to include
0	*macTRLEenabled*	Header	TRLE Descriptor (S.5.1.1)

5.2.2.8 LE-multipurpose Wake-up frame

5.2.2.8.1 General

Replace Figure 48m with the following new figure:

Octets: 2	1	2	2	4/6	2
Frame Control	Sequence Number	Destination PAN ID	Destination Address	RZ Time Header IE	IE List Terminator

Figure 48m—Multipurpose Wake-up frame

5.2.4 Information element

5.2.4.2 Header information elements

Change Table 4b (the entire table is not shown) as indicated:

Table 4b—Element IDs, Header IEs

Element ID	~~Content length~~	Name	Description
0x1d	~~2~~	RZ Time	As ~~D~~defined in 5.2.4.10
0x21		Extended DSME PAN Descriptor	As defined in 5.2.4.9a
0x22		MPDU Fragment Sequence Context Description	As defined in 5.2.4.25
0x23		Simplified Superframe Specification	As defined in 5.2.4.26
0x24		Simplified GTS Specification	As defined in 5.2.4.27
0x25		LECIM Capabilities	As defined in 5.2.4.28
0x26		TRLE Descriptor	As defined in S.5.1.1
~~0x21~~0x27–0x7d	—	Reserved	—

5.2.4.5 MLME information elements

Change Table 4d (the entire table is not shown) as indicated:

Table 4d—Sub-ID allocation for short form

Sub-ID value	~~Content length~~	Name	Description
0x27		PCA Info	Description of the LECIM PCA allocation parameters in use, as described in 5.2.4.21a.
0x28		DSSS Operating Mode	Description of the operating mode parameters for the DSSS LECIM PHY, as defined in 5.2.4.29.1.
0x29		FSK Operating Mode	Description of the operating mode parameters for the FSK LECIM PHY, as defined in 5.2.4.29.2.
~~0x27~~0x2a–0x3f	—	Reserved	—

5.2.4.7 LE CSL IE

Replace Figure 48t with the following new figure.i:

Octets: 2	2	2
CSL Phase	CSL Period	RZ Time

Figure 48t—Format of the LE CSL IE

Insert the following new paragraph at the end of 5.2.4.7

The RZ Time field is only present in the transmitted IE when *macCSLInterval* is nonzero. The RZ Time field is the expected length of time, in units of 10 symbols, between the end of the transmission of the wake-up frame and the beginning of the transmission of the payload frame. When the CSL receives a data request frame from the corresponding destination device, the MAC sublayer shall send enhanced acknowledgements with the RZ Time field updated to zero.

5.2.4.9.5 Group ACK specification

Insert the following new subclause (5.2.4.9a) after 5.2.4.9.5:

5.2.4.9a Extended DSME PAN descriptor IE

The format of the Extended DSME PAN Descriptor element shall be as illustrated in Figure 48ab.

Octets: 2	variable	2	8	variable	variable	0/1	variable
Superframe Specification	Pending Address	Extended DSME Superframe Specification	Time Synchronization Specification	Beacon Bitmap	Channel Hopping Specification	Hopping Sequence Length	Hopping Sequence

Figure 48ab—Format of Extended DSME PAN Descriptor IE

The Superframe Specification field is described in 5.2.2.1.2.

The Pending Address field is described in 5.2.2.1.6.

The Extended DSME Superframe Specification field shall be formatted as illustrated in Figure 48ac.

Bits: 0–7	8	9	10	11	12	13–15
MO	Channel Diversity Mode	Reserved	CAP Reduction Flag	Deferred Beacon Flag	Hopping Sequence List Flag	Reserved

Figure 48ac—Format of the Extended DSME Superframe Specification field

The MO, Channel Diversity Mode, CAP Reduction Flag, and Deferred Beacon Flag fields of the Extended DSME Superframe Specification field are described in 5.2.4.9.1.

The Hopping Sequence List Flag field of the Extended DSME Superframe Specification field shall be set to one if an association request command is received before the enhanced beacon transmission and the Hopping Sequence ID of one is used in the DSME-enabled PAN.

The Time Synchronization Specification field is described in 5.2.4.9.2.

The Beacon Bitmap field is described in 5.2.4.9.3.

The Channel Hopping Specification field is described in 5.2.4.9.4. This field is present only in the channel hopping mode (i.e., the value of the Channel Diversity Mode field in the DSME Superframe Specification is set to one).

The Hopping Sequence Length field is described in 5.3.11.3.4. This field is present only if the Hopping Sequence List Flag field of the Extended DSME Superframe Specification field is one.

The Hopping Sequence field is described in 5.3.11.3.5. This field is present only if the Hopping Sequence List Flag field of the Extended DSME Superframe Specification field is one.

5.2.4.10 Rendezvous Time IE

Change 5.2.4.10 as indicated:

The Rendezvous Time (RZ Time) IE is used in the LE Wake-up frame and shall be formatted as illustrated in Figure 48aaa.

Octets: 2	**2**
RZ Time	Wake-up Interval

Figure 48aaa—Format of the RZ Time IE

~~The Rendezvous Time (RZ Time) IE is 2 octets.~~ The RZ Time field is the expected length of time in units of 10 symbols between the end of the transmission of the wake-up frame and the beginning of the transmission of the payload frame. The RZ Time field shall be set by the next higher layer when requesting the MAC sublayer to transmit. The last wake-up frame in a wake-up sequence shall have RZ Time field set to the value zero.

The Wake-up Interval field is only present in the transmitted IE when *macCSLInterval* is nonzero. The Wake-up Interval field is the length of the interval between two successive LE wake-up frames in the wake-up sequence, in units of 10 symbols. The Wake-up Interval field shall be set to *macCSLInterval* when requesting the MAC sublayer to transmit.

5.2.4.21 Unmanaged ID space IEs

Insert the following new subclause(5.2.4.21a) after 5.2.4.21:

5.2.4.21a LECIM PCA Allocation Specification IE

The LECIM PCA Allocation Specification IE shall be formatted as shown in Figure 48ttb.

Bit: 0	**1**	**2–15**	**16–23**
PCA Used	Super-rate	Delay Tolerance	Allocation Rate

Figure 48ttb—Format of LECIM PCA Allocation Specification IE

The PCA Used field is set according to the MAC PIB attribute *macPriorityChannelAccess*, with a value of zero indicating *macPriorityChannelAccess* is FALSE and a value of one indicating *macPriorityChannelAccess* is TRUE.

The Super-rate field is set according to the MAC PIB attribute *macPCAAllocationSuperRate* with a value of zero indicating *macPCAAllocationSuperRate* is FALSE and a value of one indicating *macPCAAllocationSuperRate* is TRUE.

The Delay Tolerance field describes the delay tolerance of a critical event message, encoded as an integer in units of $60.0/(2^{14}-1)$ seconds.

The Allocation Rate field is set according to the MAC PIB attribute *macPCAAllocationRate,* and in conjunction with *macPCAAllocationSuperRate*, it provides the rate at which PCA allocations are made, as described in 5.1.1.4.5.

5.2.4.24 O-QPSK PHY Operating Mode Description IE

Insert the following new subclauses (5.2.4.25–5.2.4.29.2) after 5.2.4.24:

5.2.4.25 MPDU Fragment Sequence Context Description IE

The MPDU Fragment Sequence Context IE contains a description of an MPDU being fragmented and associates this information with a unique fragmentation transaction identifier (TID). The format of the MPDU Fragment Sequence Context Description IE is given in Figure 48ww.

Octets: 2						**2**		
Bits: 1	**1**	**5**	**6**	**2**	**1**	**10**	**6**	
Fragment Tx Option	Secure Fragment	Reserved	TID	I-ACK Policy	TID Extension	MPDU Size / Success Threshold	Addressing Information	...

	0/1/3/5	**variable**	**0/4**		**0/2**
			26	**6**	
...	TID Extension Parameters	Addressing	MPDU Counter	Reserved	PHY-dependent Parameters

Figure 48ww—Format of the MPDU Fragment Sequence Context Description IE

5.2.4.25.1 Fragment Tx Option field

When *macExtendedDSMEenabled* is set to TRUE, the Fragment Tx Option field indicates whether subsequent transmissions or retransmissions of fragments occur in the next available CAP or in the next DSME-GTS allocated, if the transmission of fragments is not completed in a DSME-GTS. Subsequent fragments shall be transmitted or retransmitted in the next available CAP if the field is set to zero.

Subsequent fragments shall be transmitted or retransmitted in the next DSME-GTS allocated if the field is set to one.

5.2.4.25.2 Secure Fragment field

The Secure Fragment field is used to indicate whether the fragments in this transaction will be sent with authentication. When set, the MPDU Counter field shall be present in this IE, and the fragment validation field shall be set to the MIC, as described in 7.4. The field shall be set to one when *macMPDUFragSecure* is set to TRUE.

5.2.4.25.3 TID field

A TID field value of zero indicates that the TID field will not be present in the fragments that follow. When the TID field value is nonzero, the value identifies the fragment sequence. It associates the context information with each fragment in the transaction. The specific method for generating the TID is implementation dependent and should assure that the current value is different from the preceding value.

5.2.4.25.4 I-ACK Policy field

The I-ACK Policy field shall be set to one of the following values given in Table 4t.

Table 4t—I-ACK Policy field values

I-ACK Policy field value	MPDU Size/ Success Threshold field	I-ACK policy description
0	Number of octets in the MPDU	An I-ACK shall be sent upon reception of each fragment
1	Number of octets in the MPDU	ACK/NACK based on time: An I-ACK shall be generated if *macIACKprogressTimeout* has elapsed since the reception of the fragment context frame or the last received fragment, whichever is later.
2	Number of octets in the MPDU	ACK "last outstanding" fragment: An I-ACK shall be generated only when the last expected fragment is received, or if *macIACKprogressTimeout* has elapsed since the last received fragment.
3	Number of valid fragments required to be received in order to declare the transaction successful	ACK after specified number of known good fragments received: The I-ACK shall be generated after the successful reception of at least the number of fragments specified in the MPDU Size/Success Threshold field have been received and validated.

5.2.4.25.5 TID Extension field

The TID Extension field shall be set to one to indicate that the TID Extension Parameters field is present. Otherwise, the TID Extension Parameters field is absent.

5.2.4.25.6 MPDU Size/Success Threshold field

The MPDU Size/Success Threshold field is described in Table 4t.

5.2.4.25.7 Addressing Information field

The Addressing Information field describes the content of the addressing fields that follow. The fragment context frame description may contain any combination of source PAN ID, destination PAN ID, source address, and destination address in any of the allowable addressing modes defined by this standard. Figure 48xx illustrates the format of this field.

Bit: 0	1	2–3	4–5
Source PAN ID Present	Destination PAN ID Present	Source Address Mode	Destination Address Mode

Figure 48xx—Addressing Information field format

The setting of the Addressing Information field shall be determined by the PAN ID and addressing mode fields of the MPDU being fragmented.

The Source and Destination PAN ID Present fields shall be set respectively if a source and/or destination PAN ID is included in the Addressing field. The Source Address Mode field indicates the presence and format of a source address included in the Addressing field; the Source Address Mode field shall be set to one of the values given in Table 3. The Destination Address Mode field shall indicate the presence and format of a destination address included in the Addressing field, and the Destination Address Mode field shall be set to one of the values given in Table 3.

5.2.4.25.8 TID Extension Parameters field

The TID Extension Parameters field is present only when the TID Extension field is set. When present, the field shall be encoded as shown in Figure 48yy. The TID Extension Parameters field may be used to enhance unique identification of the transaction by reducing the probability that the TID will be decoded and recognized by devices other than the intended device.

Bits: 1	7	16 or 32
FVS RIV Present	FVS Offset Value	FVS RIV

Figure 48yy—TID Extension Parameters field format

The FVS Remainder Initialization Value (RIV) Present field shall be set to one to indicate that the FVS RIV field is present. It shall be set to zero otherwise.

The FVS Offset Value field indicates whether the location of the FVS value is offset within the PHY service data unit (PSDU), and the field contains the value of the offset in octets. A value of zero indicates that no offset was used, (i.e., the FVS value is located at the end of the PSDU). A value greater than zero indicates that the FVS value is offset within the PSDU; the offset value is counted back from the last octet of the PSDU. If the FVS offset feature is not supported by a receiving device, the receiving device shall ignore any fragment or I-ACK received with this field set to a value greater than zero.

The FVS RIV field is only present if the value used as the initial remainder in the CRC calculation is not equal to the default initialization value for the remainder given in 5.2.1.9. In a transmitting device, this field is used to signal that an alternate CRC RIV was used when generating the fragment or I-ACK. In a receiving device, when a FVS RIV value other than zero is present, the CRC calculation initial value shall be set to the FVS RIV field contents. The length of the field is determined by the current value of *macFragmentFVSType*.

In order to allow for alternative coordination methods, the TID extension methods for FVS offset and FVS RIV may be determined by the *macFVSoffset* and *macFVSRIV* PIB attributes and not signaled in the MPDU Fragment Sequence Context Description IE. In the event that an MPDU Fragment Sequence Context Description IE is received with a value different than what is set in the PIB, the received values shall be used for that transaction.

5.2.4.25.9 Addressing field

The Addressing field contains source and/or destination addressing information associated with the MPDU being fragmented. The format is illustrated in Figure 48zz.

Octets: 0/16	0/16	0/8/16/64	0/8/16/64
Source PAN ID	Destination PAN ID	Source Address	Destination Address

Figure 48zz—Addressing field format

The content of this field shall be set according to the addresses contained in the MHR of the MPDU being fragmented. Addresses may be elided to fit into the PSDU size of the PHY in use; algorithms for address suppression are implementation-dependent.

5.2.4.25.10 MPDU Counter field

The MPDU Counter field shall be present when the Secure Fragment field is set to one (*macMPDUFragSecure* is set to TRUE). The MAC shall maintain a counter that is incremented with each MPDU fragmentation transaction, initiated such that the counter value is not repeated, as described in 7.4.2.

5.2.4.25.11 PHY-dependent Parameters field

The value of the PHY-dependent Parameters field depends upon the PHY being used. The possible values are implementation dependent. For the LECIM FSK PHY defined in 19.2, this field is 2 octets in length and contains the fragment size used for the transaction. This field is not used by the LECIM DSSS PHY.

5.2.4.26 Simplified Superframe Specification IE

The Simplified Superframe Specification IE may be used to define a basic superframe in a format that can be transmitted in the smallest single PSDU provided for by the LECIM PHYs, such that it may be transmitted unfragmented. The Simplified Superframe Specification IE shall be formatted as shown in Figure 48aaa.

Octets: 2	2	2
Timestamp	Superframe Specification	CFP Specification

Figure 48aaa—Format of the Simplified Superframe Specification IE

The Timestamp field shall be incremented between transmissions; the initial value, resolution (LSB value), and accuracy are implementation dependent.

The Superframe Specification field is as defined in 5.2.2.1.2.

The Contention-Free Period (CFP) Specification field determines the size and position of the CFP and CAP within the superframe. The CFP Specification field shall be encoded as shown in Figure 48aab.

Bits: 0–3	4–7	8–11	12	13–15
Number of GTSs	First CFP Slot in Superframe	Last CFP Slot in Superframe	GTS Permit	Reserved

Figure 48aab—CFP Specification field format

Each GTS contains an equal number of superframe slots. The Number of GTSs field is set according to the number of GTSs allocated by the coordinator. The value of the First CFP Slot in Superframe field is equal to the slot number in which the CFP begins. The value of the Last CFP Slot in Superframe field is equal to the slot number in which the CFP ends.

The GTS Permit field shall be set to one if *macGTSPermit* is equal to TRUE, indicating that the coordinator is accepting GTS requests. Otherwise, the field shall be set to zero.

5.2.4.27 Simplified GTS Specification IE

The Simplified GTS Specification IE, shown in Figure 48aac, and the Simplified Superframe Specification IE, shown in Figure 48aaa, indicate devices that have been allocated a GTS.

Octets: 1	Variable
GTS Directions	GTS Device Address List

Figure 48aac—Format of the Simplified GTS Specification IE

The GTS Directions field is defined in Figure 43 of 5.2.2.1.4.

The GTS Device Address List field contains one address for each GTS defined as indicated in the Number of GTSs field in the Simplified Superframe Specification IE. Each GTS device address list entry is a short (i.e., 16-bit) address assigned to the device that has been granted the GTS. If a GTS has not been allocated, the address list entry for that slot shall contain the value 0xffff.

5.2.4.28 LECIM Capabilities IE

The following IE declares the LECIM capabilities supported by a device. The presence of this IE in a transmitted frame indicates that the device supports a LECIM PHY. The IE content shall be as shown in Figure 48aad.

Octets: 2	2	0/2	0/2
PHY Type and Bands Supported	LECIM PHY Features Supported	Lowest 2.4 GHz Channel	Highest 2.4 GHz Channel

Figure 48aad—Format of the LECIM Capabilities IE

In the PHY Type and Bands Supported field, bit 0 indicates the PHY type supported, which is the PHY type being described by the IE. A value of one indicates that LECIM FSK is described; a value of zero indicates that LECIM DSSS is described. Bits 1–11 indicate support for different bands. A value of one indicates that a band is supported; a value of zero indicates that a band is not supported. The device shall indicate as supported only those bands that are implemented and defined for the indicated PHY type. The encoding for the field is shown in Table 4u.

Table 4u—LECIM PHY Type and Bands Supported field encoding

Bit number	Description
0	PHY type described: 0 = LECIM DSSS 1 = LECIM FSK
1	Band 169 supported
2	Band 433 supported
3	Band 470 supported
4	Band 780 supported
5	Band 863 supported
6	Band 915 supported
7	Band 917 supported
8	Band 920 supported
9	Band 921 supported
10	Band 922 supported
11	Band 2450 supported
12–15	Reserved

When the PHY Type and Bands Supported field indicates a LECIM DSSS PHY, the LECIM PHY Features Supported field shall be encoded as shown in Table 4v. Bit 0 and bit 1 indicate support for different modulation schemes. A value of one indicates that the modulation scheme is supported; a value of zero indicates that the modulation scheme is not supported. Bits 2–5 indicate that maximum spreading factor is supported. The valid value range is between 16 and 32768 and is calculated by:

$$2^{(\text{bits 2–5})_{10}}$$

Bits 6–8 indicate support for different PSDU sizes. A value of one indicates that the PSDU size is supported; a value of zero indicates that PSDU size is not supported.

Table 4v—LECIM PHY Features Supported field encoding for DSSS

Bit number	Description
0	BPSK modulation supported
1	O-QPSK modulation supported
2–5	Maximum spreading factor supported; see Table 71 for the definition of *phyLECIMDSSSPSDUSpreadingFactor*.
6	16 octet PSDU supported
7	24 octet PSDU supported
8	32 octet PSDU supported
9	OVSF supported
10–15	Reserved

When the PHY Type and Bands Supported field indicates a LECIM FSK PHY, the LECIM PHY Features Supported field shall be encoded as shown in Table 4w. A value of one indicates that the feature is supported; a value of zero indicates that the feature is not supported.

Table 4w—LECIM PHY Features Supported field encoding for FSK

Bit number	Description
0	Positional modulation supported
1	Symbol rate 37.5 ksps supported, 200 kHz channel spacing [a]
2	Symbol rate 25 ksps supported, 200 kHz channel spacing [a]
3	Symbol rate 12.5 ksps supported, 200 kHz channel spacing [a]
4	Symbol rate 37.5 ksps supported, 100 kHz channel spacing [a]
5	Symbol rate 25 ksps supported, 100 kHz channel spacing [a]
6	Symbol rate 12.5 ksps supported, 100 kHz channel spacing [a]
7	FEC supported
8	Interleaving supported
9	Scrambling supported
10	SF 2 supported
11	SF 4 supported
12	SF 8 supported
13	SF 16 supported

Table 4w—LECIM PHY Features Supported field encoding for FSK *(continued)*

Bit number	Description
14	Alternating SF pattern supported
15	Non-alternating SF pattern supported

[a]Defined in 19.2.2.

The Lowest 2.4 GHz Channel and the Highest 2.4 GHz Channel fields specify the range of channels within the 2.4 GHz band supported. These fields shall only be present when the PHY Type and Bands Supported field indicates support for the 2.4 GHz band. The range includes all of the channels starting from the channel number specified in the Lowest 2.4 GHz Channel field to the channel number specified in the Highest 2.4 GHz Channel field, inclusive.

5.2.4.29 Operating Mode Description IEs

5.2.4.29.1 DSSS Operating Mode Description IE

The DSSS Operating Mode Description IE content shall be encoded as shown in Table 4x.

Table 4x—Operating Mode Information field encoding for DSSS

Bit number	Description
0–3	Operating band selected. The bands are defined as the integers greater than 0 corresponding to the bit numbers given in Table 4u. Not all entries are valid. Values not corresponding to a band ID in Table 4u are reserved.
4–12	Channel number, as defined in 8.1.2.
13	Modulation selection: 0 = BPSK 1 = O-QPSK
14–16	Chip rate in kchip/s: 0 = invalid 1 = 100 2 = 200 3 = 400 4 = 600 5 = 800 6 = 1000 7 = 2000
17	Channel spacing, as specified in Table 68l. 0 = 0.1 MHz 1 = 0.2 MHz
18–19	PSDU size: 00 = invalid 01 = 16 octets 10 = 24 octets 11 = 32 octets

Table 4x—Operating Mode Information field encoding for DSSS *(continued)*

Bit number	Description
20	Preamble present: 0 = not present 1 = present
21	Start-of-frame delimiter (SFD) present: 0 = not present 1 = present
22–25	Spreading factor; see Table 71 for the definition of *phyLECIMDSSSPSDUSpreadingFactor*.
26–29	OVSF spreading factor: 0000 = OVSF not applied 0001 = SF of 2 0010 = SF of 4 0011 = SF of 8 0100 = SF of 16 0101 = SF of 32 0110 = SF of 64 0111 = SF of 128 1000 = SF of 256
30–53	Gold code LFSR2 initialization value, as specified in 19.1.2.6.1.
54–63	Reserved

5.2.4.29.2 FSK Operating Mode Description IE

The FSK Operating Mode Description IE content shall be encoded as shown in Table 4y.

Table 4y—Operating Mode Information field encoding for FSK

Bit number	Description
0–3	Operating band selected. The bands are defined as the integers greater than 0 corresponding to the bit numbers given in Table 4u. Not all entries are valid. Values not corresponding to a band ID in Table 4u are reserved.
4–12	Channel number, as defined in 8.1.2.
13	Position modulation utilized.
14–15	Symbol rate: 0 = 37.5 ksps 1 = 25 ksps 2 = 12.5 ksps
16	Channel spacing: 0 = channel spacing for indicated operating band is 200 kHz 1 = channel spacing for indicated operating band is 100 kHz
17	FEC enabled: 0 = not enabled 1 = enabled

Table 4y—Operating Mode Information field encoding for FSK *(continued)*

Bit number	Description
18	Interleaving enabled: 0 = not enabled 1 = enabled
19	Scrambler enabled: 0 = not enabled 1 = enabled
20	Spreading enabled: 0 = not enabled 1 = enabled
21–22	Spreading factor (see definition of *phyLECIMDSSSPSDUSpreadingFactor*): 0 = SF of 2 1 = SF of 4 2 = SF of 8 3 = SF of 16
23	Spreading pattern: 0 = non-alternating 1 = alternating
24–31	Reserved

5.3 MAC command frames

Change Table 5 (the entire table is not shown) as indicated:

Table 5—MAC command frames

Command frame identifier	Command name	RFD		Subclause
		Tx	Rx	
0x0a	TRLE-Management request	X	X	S.5.2.1
0x0b	TRLE-Management response	X	X	S.5.2.2
0x0c–0xff ~~0x21–0x3f~~	Reserved			—
~~0x44–0x5f~~	~~Reserved~~			—
~~0x61–0x62~~	~~Reserved~~			—
~~0x64–0xff~~	~~Reserved~~			—

5.3.11 DSME-commands

5.3.11.2 DSME-Association request command

Replace Figure 59g with the following figure:.

Octets: variable (5.2.2.4.1)	1	1	1	2	0/1
MHR fields	Command Frame Identifier	Capability Information	Hopping Sequence ID	Channel Offset	Extended DSME-GTS Allocation

Figure 59g—DSME-Association request command format

5.3.11.2.2 Capability Information field

Change the first paragraph of 5.3.11.2.2 as indicated and insert the new figure (Figure 59ga):

The Capability Information field shall be formatted as ~~described in 5.3.1.2~~ illustrated in Figure 59ga.

Bits: 0	1	2	3	4	5	6	7
Reserved	Device Type	Power Source	Receiver On When Idle	DSME Association Type	Reserved	Security Capability	Allocate Address

Figure 59ga—Capability Information field format

Insert the following two new paragraphs at the end of 5.3.11.2.2:

The Device Type field, Power Source field, Receiver On When Idle field, Security Capability field, and Allocate Address field are described in 5.3.1.2.

The DSME Association Type field shall be set to one if a device requests assignment of a DSME-GTS by a coordinator during association. Otherwise, the DSME Association Type field shall be set to zero.

5.3.11.2.4 Channel Offset field

Insert the following new subclause (5.3.11.2.5) after 5.3.11.2.4:

5.3.11.2.5 Extended DSME-GTS Allocation field

The Extended DSME GTS Allocation field shall be present if *macExtendedDSMEenabled* is TRUE and the value of the DSME Association Type field is one. This field shall be formatted as illustrated in Figure 59gb.

Bits: 0	1–4	5–7
Direction	Allocation Order	Reserved

Figure 59gb—Extended DSME-GTS Allocation field format

The Direction field specifies the direction of the DSME-GTSs, which is relative to the data flow from the requesting device. The direction is specified as either transmit or receive. The value of this field shall be set to zero if the allocation is for transmission. The value shall be set to one if the allocation is for reception.

The Allocation Order field is described in 5.3.11.3.6.

5.3.11.3 DSME-Association response command

Replace Figure 59h with the following figure5.3.11.3.10:

Octets: variable	**1**	**2**	**1**	**0/1**	**variable**	**0/1**	**0/1**	**0/2**	**0/1**	**0/2**
MHR fields	Command Frame Identifier	Short Address	Association Status	Hopping Sequence Length	Hopping Sequence	Allocation Order	BI Index	Superframe ID	Slot ID	Channel Index

Figure 59h—DSME-Association response command format

5.3.11.3.4 Hopping Sequence Length field

Change the first paragraph of 5.3.11.3.4 as indicated:

The Hopping Sequence Length field shall specify the length of the Hopping Sequence used in the PAN if the PAN runs in both beacon-enabled mode and Channel Hopping mode, i.e., ChannelDiversityMode of one. When the value of HoppingSequenceID is other than one or DSMEAssociationType is one, this field shall be set to zero. The Hopping Sequence field shall be present only if the value of the Hopping Sequence Length field is not zero.

5.3.11.3.5 Hopping Sequence field

Insert the following new subclauses (5.3.11.3.6–5.3.11.3.10) after 5.3.11.3.5:

5.3.11.3.6 Allocation Order field

The Allocation Order field shall be present if *macExtendedDSMEenabled* is TRUE and the DSMEAssociationType parameter of the device requesting association is set to one. This field shall indicate the DSME-GTS allocation interval and be set to the value of AllocationOrder, AO, of the device requesting association. The value of AO and the DSME-GTS allocation interval are related as follows:

$$\text{DSME-GTS allocation interval} = \mathrm{BI} \times 2^{(\mathrm{MO}-\mathrm{BO})} / 2^{\mathrm{AO}} \quad \text{for } \mathrm{MO} > \mathrm{BO}$$

If $\mathrm{MO} \leq \mathrm{BO}$, the DSME-GTS allocation interval is the same as an MD.

5.3.11.3.7 BI Index field

The BI Index field shall be present if *macExtendedDSMEenabled* is TRUE and the DSMEAssociationType parameter of the device requesting association is set to one. This field shall contain the index of the beacon interval *macBIIndex*, BI, in which the DSME-GTS needs to be allocated. The BI Index is the sequence number of the BI in a multi-superframe beginning from zero.

A device can locate the value of BI Index in which the DSME-Associate response command is received by using the value of *macPANCoordinatorBSN* as follows:

$$\text{BI Index} = macPANCoordinatorBSN \ \% \ 2^{(\text{MO} - \text{BO})}$$

5.3.11.3.8 Superframe ID field

The Superframe ID field shall be present if *macExtendedDSMEenabled* is TRUE and the DSMEAssociationType parameter of the device requesting association is set to one. This field shall contain the index of the superframe in which the DSME-GTS needs to be allocated. The Superframe ID is the sequence number of the superframe in a multi-superframe beginning from zero. The superframe in which the PAN coordinator sends its beacons serves as the reference point (Superframe ID 0). An example of superframe IDs is illustrated in Figure 34h.

5.3.11.3.9 Slot ID field

The Slot ID field shall be present if *macExtendedDSMEenabled* is TRUE and the DSMEAssociationType parameter of the device requesting association is set to one. This field shall contain the index of the DSME-GTS to be allocated. The slot ID is the sequence number of the DSME-GTS in a superframe beginning from zero. An example of slot IDs is illustrated in Figure 34h.

5.3.11.3.10 Channel Index field

The Channel Index field shall be present if *macExtendedDSMEenabled* is TRUE and the DSMEAssociationType parameter of the device requesting association is set to one. This field shall contain the channel number of the DSME-GTS to be allocated.

5.3.11.4 DSME-GTS request command

5.3.11.4.1 General

Replace Figure 59i with the following figure:

Octets: variable (refer to 5.2.2.4.1)	**1**	**1**	**0/1**	**0/2**	**0/1**	**Variable**	**0/1**
MHR fields	Command Frame Identifier (defined in Table 5)	DSME-GTS Management	Number of Slots	Preferred Superframe	Preferred Slot ID	DSMESAB-Specification	Allocation Order

Figure 59i—DSME-GTS request command format

5.3.11.4.7 DSMESABSpecification field

Add the following new subclause (5.3.11.4.8) after 5.3.11.4.7:

5.3.11.4.8 Allocation Order field

The Allocation Order field shall be present if *macExtendedDSMEEnabled* is TRUE. This field shall indicate the DSME-GTS allocation interval and be set to the value of AllocationOrder of the device requesting a DSME-GTS. The relationship between the value of this field and the DSME-GTS allocation interval is described in 5.3.11.3.6.

5.3.11.5 DSME-GTS reply command

5.3.11.5.1 General

Replace Figure 59l with the following figure:

Octets: variable (refer to 5.2.2.4.1)	**1**	**1**	**2**	**0/2**	**Variable**	
MHR fields	Command Frame Identifier (defined in Table 5)	DSME-GTS Management	Destination Address	Channel Offset	DSMESABSpecification	...

	0/1	**0/1**	**0/2**	**0/1**	**0/2**
...	Allocation Order	BI Index	Superframe ID	Slot ID	Channel Index

Figure 59l—DSME-GTS reply command format

5.3.11.5.6 DSMESABSpecfication fields

Add the following new subclauses (5.3.11.5.7–5.3.11.5.11) after 5.3.11.5.6:

5.3.11.5.7 Allocation Order field

The Allocation Order field shall be present if *macExtendedDSMEEnabled* is TRUE. This field shall indicate the DSME-GTS allocation interval and be set to the value of AllocationOrder of the device requesting a DSME-GTS. The relationship between the value of this field and the DSME-GTS allocation interval is described in 5.3.11.3.6.

5.3.11.5.8 BI Index field

The BI Index field shall be present if *macExtendedDSMEenabled* is TRUE. This field shall contain the index of the beacon interval *macBIIndex*, BI, in which the DSME-GTS needs to be allocated. The BI Index is the sequence number of the BI in a multi-superframe beginning from zero.

5.3.11.5.9 Superframe ID field

The Superframe ID field shall be present if *macExtendedDSMEenabled* is TRUE. This field shall contain the index of the superframe in which the DSME-GTS is to be allocated. The Superframe ID is the sequence number of the superframe in a multi-superframe beginning from zero. The superframe in which the PAN coordinator sends its beacons serves as the reference point (Superframe ID 0).

5.3.11.5.10 Slot ID field

The Slot ID field shall be present if *macExtendedDSMEenabled* is TRUE. This field shall contain the index of the DSME-GTS to be allocated. The Slot ID is the sequence number of the DSME-GTS in a superframe beginning from zero.

5.3.11.5.11 Channel Index field

The Channel Index field shall be present if *macExtendedDSMEenabled* is TRUE. This field shall contain the channel number of the DSME-GTS to be allocated.

5.3.13.3.2 Channel Probe Specification Field

Insert the following new subclauses (5.4–5.4.2.1.2) after 5.3.13.3.2:

5.4 MPDU fragmentation

Devices that support the LECIM DSSS PHY shall support MPDU fragmentation. Support for MPDU fragmentation is optional for all other PHYs.

When *macMPDUFragmentationEnabled* is TRUE, the MPDU is processed into a sequence of fragments. The context of the fragment sequence is established by transmitting a fragment context frame between the initiating device and the recipient device prior to transmission. Each fragment containing an FVS, a fragment descriptor, and fragment content is packaged into a PPDU.

5.4.1 MPDU fragmentation and reassembly

5.4.1.1 Fragment sequence context

The fragment sequence context is established by transmitting a fragment context frame containing an MPDU Fragment Sequence Context Description IE, as described in 5.2.4.25. A fragment context frame is any directed MAC command or data frame which contains exactly one MPDU Fragment Sequence Context Description IE.

The fragment context frame initiates the transaction and establishes the initial state for the MPDU fragment sequence transaction. The fragment context frame shall be transmitted with the Acknowledge Request field set to one. If an acknowledgment is not received, the fragment context frame shall be retransmitted up to *macMaxFrameRetries* times as needed. If an acknowledgment is received, the initiating device transmits the fragments until either the transaction is complete or the transmission is aborted.

Upon reception of the fragment context frame, the information contained within the frame is associated with the value of the TID information in the MPDU Fragment Context Description IE, and that TID information is used to identify subsequent fragments in the sequence.

A PHY may provide alternate means to establish an exclusive link context, in which case the TID field may be elided from each fragment. A TID field value of zero in the context description frame shall be used to indicate that the TID field is not present in the fragments during that transaction; this value should be used only with PHYs that support other means to establish exclusive link context.

When the fragment context frame is received with the Secure Fragment field set to one, the MPDU Counter field shall be used with the fragment number to form the Frame Counter field used to construct the nonce, as described in 7.2.1, except that *macFrameCounter* is replaced with *macFragmentFrameCounter*. The PIB attribute *macFragmentFrameCounter* shall be comprised of the MPDU counter field, used as the most significant 26 bits, and the fragment number, used as the least significant 6 bits.

5.4.1.2 Fragment format

The fragment format is depicted in Figure 59dda.

Octets: 2			**variable**	**2/4**
Bits: 0–2	**3–9**	**10–15**		
Frame Type	TID0–TID6	Fragment Number	Fragment Data	FVS
Fragment header				

Figure 59dda—Fragment format

The Frame Type field differentiates a fragment from an unfragmented frame. The value of the Frame Type field shall be set to 110.

The TID field shall contain the value assigned to the transaction context, as indicated in the fragment context frame. When context is unambiguously known via other means provided by the PHY in use, the TID field may be omitted. Upon reception, if the TID field contains a value other than the TID of a currently active transaction, the cell is ignored (i.e., not acknowledged and not counted to reset the transaction timeout).

The Fragment Number field identifies the fragment contained in the Fragment Data field. Upon MPDU reassembly, the fragmented data shall be placed in order according to fragment number. A Fragment Number field value of 0x3f is reserved for future use.

The Fragment Data field contains the part of the fragmented MPDU indicated by the Fragment Number field. The size of the data field depends on the configuration of the PHY in use.

The FVS field is used to validate the received fragment. When *macMPDUFragSecure* is FALSE, the length of the field shall be determined by *macFragmentFVSType*, and it shall be calculated according to 5.2.1.9, except that the initial remainder value used for CRC calculation shall be as described in 5.2.4.25.8. When *macMPDUFragSecure* is TRUE, the length of the field shall be 4 octets and shall contain the MIC-32, as described in 5.4.1.1.

5.4.1.3 Fragmentation

The MPDU is prepared for fragment transmission according to the following steps:

a) Determine the fragment sequence context.
b) Determine the TID.
c) Construct the fragment context frame, as described in 5.4.1.1.
d) Divide the remaining MPDU into fragments of the size supported by the current PHY configuration. All fragments, with the exception of the final fragment, shall contain the maximum number of data octets. For PHY configurations that use a fixed PPDU size (i.e., no PPDU length field transmitted),

the final fragment data shall be padded with *macMPDUFragPadValue*; the FVS field for the final fragment shall be calculated including the pad octets. When a PHY configuration only supports a fixed size PSDU, the size of each fragment shall be the PSDU size configured for that PHY; for all other PHYs, the fragment size shall be equal to the value of *macFragmentSize*.

e) Transmit the fragment context frame (retransmit as necessary).

f) Upon acknowledgment of the fragment context frame, transmit the fragments. Wait for the I-ACK cells according to the I-ACK policy value, described in 5.2.4.25.4, which is specified in the fragment context frame. Retransmit the cell preceding the I-ACK if the acknowledgment is not received within the I-ACK timeout period.

g) Upon reception of the final fragment and/or transmission of the final I-ACK as appropriate, the reassembled MPDU is processed as described in 5.1.6.

Fragments shall be transmitted after the Fragment Context Frame, beginning with fragment 1 and ending with fragment *n*. The I-ACK is described in 5.4.2.1. If the I-ACK retransmission count is exceeded during the transaction, the transaction is terminated and a fragment with the Fragment Number field set to zero is transmitted to signal the receiving device.

5.4.1.4 Reassembly

Upon reception of the fragment context frame, the transaction state is initialized for a new MPDU fragment sequence transaction, and the fragment context frame is acknowledged. Each received fragment is placed into the reassembled MPDU based on the value of the corresponding Fragment Number field. I-ACKs are generated according to 5.4.2.1. When the final fragment is received and validated, the MPDU validation (FCS) is presumed successful (without requiring an FCS of the frame) and processing proceeds according to 5.1.6.4.2.

5.4.2 Fragment acknowledgment and retransmission

Two levels of acknowledgment are provided: acknowledgment of fragments during the transfer process (i.e., I-ACK), which provide “progress reports”; and acknowledgment of the reassembled MPDU, as described in 5.1.6.4.2.

5.4.2.1 I-ACK

The I-ACK reports status indicating which fragments have been successfully received up to that point, and it is generated incrementally during the fragment sequence transfer according to the I-ACK policy provided in the context setup.

5.4.2.1.1 I-ACK overview

The interval of the I-ACK is determined by the I-ACK Policy field, which is transmitted to the receiving device in the fragment sequence context, as defined in 5.4.1.1. Upon completing the transmission of the fragment preceding the expected I-ACK according to the I-ACK policy selected, the initiating device shall suspend transmission and wait for the expected I-ACK. Upon reception of the I-ACK, fragments indicated as not received correctly shall be retransmitted. The number of retransmissions shall be limited by *macMaxFrameRetries*.

Upon reception of a fragment, the FVS is validated. The receiving device shall generate an I-ACK according to the I-ACK policy in use, as described in 5.2.4.25.4; the I-ACK shall be transmitted at the next transmit opportunity following the triggering condition.

When I-ACK policy zero is in use, reception of an out-of-order fragment shall result in termination of the transaction.

5.4.2.1.2 I-ACK format

The I-ACK format shall be as depicted in Figure 59ddb.

Octets: 2			variable	2/4
Bits: 0–2	**3–9**	**10–15**		
Frame Type	TID0–TID6	Fragment Number	Fragment Status	I-ACK Validation
I-ACK header				

Figure 59ddb—I-ACK format

The Frame Type field and TID field are formatted as defined in 5.4.1.2.

The TID field shall contain the same value as the TID in the received fragments being acknowledged.

The Fragment Number field is set to the value of the last fragment received prior to I-ACK generation.

The Fragment Status field shall be as shown in Figure 59ddc.

Bits: 8	4	16/32/48/64
I-ACK Content	Link Quality Indication	Fragments Received (Set 0–Set 3)

Figure 59ddc—Fragment Status field

The I-ACK Content field shall be as shown in Table 7a. This field indicates which fragment status flags are included in the Fragment Status field. A value of one in a bit position indicates that the corresponding set of 16 status flags is present; a value of zero in a bit position indicates that the corresponding set of 16 status flags is absent. Setting all bit positions to zero indicates an aborted transaction. Bit b_0 is transmitted first in time.

Table 7a—I-ACK Content field

Bit position	Description
b_0	Indicates whether fragment status flags 0–15 are present
b_1	Indicates whether fragment status flags 16–31 are present
b_2	Indicates whether fragment status flags 32–47 are present
b_3	Indicates whether fragment status flags 48–63 are present

The Link Quality Indication field contains an indication of the signal quality of the received fragment(s) being acknowledged. The measurement method is implementation-dependent, and at least eight unique values of LQI should be provided.

The Fragments Received field indicates the status of received fragments up to the current point in the transaction. The status flags are grouped into four sets of 16, 1-bit flags. Flags for fragment numbers 0–15 are contained in Set 0, flags for fragment numbers 16–31 are contained in Set 1, flags for fragment numbers 32–47 are contained in Set 2, and flags for fragment numbers 48–63 are contained in Set 3. Within each set, the individual flags are ordered such that s_0, the first bit transmitted/received in time, corresponds to the lowest numbered fragment number in the set. When more than one set is included in the I-ACK, the lowest numbered set is transmitted first in time, so that the corresponding fragment numbers go from low to high as transmitted.

The I-ACK Validation field is used to validate the received I-ACK. The length of the field shall be determined by *macFragmentFVSType*, and it shall be calculated according to 5.2.1.9, except that the initial remainder value used for CRC calculation shall be as described in 5.2.4.25.8.

6. MAC services

6.2 MAC management service

The first paragraph of subclause 6.2 is reproduced here to assist the reader in understanding the special symbols in Table 8. No changes are made to this paragraph.

The MLME-SAP allows the transport of management commands between the next higher layer and the MLME. Table 8 summarizes the primitives supported by the MLME through the MLME-SAP interface. Primitives marked with a diamond (♦) are optional for an RFD. Primitives marked with an asterisk (*) are optional for both device types (i.e., RFD and FFD). The primitives are discussed in the subclauses referenced in the table.

Insert the following new row at the end of Table 8:

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

Name	Request	Indication	Response	Confirm
MLME-PHY-OP-SWITCH*	6.2.22.1	6.2.22.3		6.2.22.2

6.2.2 Association primitives

6.2.2.1 MLME-ASSOCIATE.request

Insert the following new parameters at the end of the list in 6.2.2.1 (before the closing parenthesis):

DSMEAssociationType,
Direction,
AllocationOrder,
HoppingSequenceRequest

Insert the following new rows at the end of Table 9:

Table 9—MLME-ASSOCIATE.request parameters

Name	Type	Valid range	Description
DSMEAssociation Type	Integer	0x00–0x01	As defined in 5.3.11.2.2.
Direction	Integer	0x00–0x01	As defined in Table 44q.
AllocationOrder	Integer	0x00–0x08	As defined in 5.3.11.3.6.
HoppingSequence Request	Boolean	TRUE, FALSE	Indicates whether a hopping sequence is requested. A value of FALSE indicates that a hopping sequence is not requested. A value of TRUE indicates that a hopping sequence is requested.

6.2.2.2 MLME-ASSOCIATE.indication

Insert the following new parameters at the end of the list in 6.2.2.2 (before the closing parenthesis):

DSMEAssociationType,
Direction,
AllocationOrder,
HoppingSequenceRequest

Insert the following new rows at the end of Table 10:

Table 10—MLME-ASSOCIATE.indication parameters

Name	Type	Valid range	Description
DSMEAssociation Type	Integer	0x00–0x01	As defined in 5.3.11.2.2.
Direction	Integer	0x00–0x01	As defined in Table 44q.
AllocationOrder	Integer	0x00–0x08	As defined in 5.3.11.3.6.
HoppingSequence Request	Boolean	TRUE, FALSE	Indicates whether a hopping sequence is requested. A value of FALSE indicates that a hopping sequence is not requested. A value of TRUE indicates that a hopping sequence is requested.

6.2.2.3 MLME-ASSOCIATE.response

Insert the following new parameters at the end of the list in 6.2.2.3 (before the closing parenthesis):

DSMEAssociationType,
AllocationOrder,
BIIndex,
SuperframeID,
SlotID,
ChannelIndex,
HoppingSequenceLength,
HoppingSequence

Insert the following new rows at the end of Table 11:

Table 11—MLME-ASSOCIATE.response parameters

Name	Type	Valid range	Description
DSMEAssociationType	Integer	0x00–0x01	As defined in 5.3.11.2.2.
AllocationOrder	Integer	0x00–0x08	As defined in 5.3.11.3.6.
BIIndex	Integer	0x00–0xff	As defined in 5.3.11.3.7.
SuperframeID	Integer	0x0000–0xffff	As defined in 5.3.11.3.8.
SlotID	Integer	0x00–0x0e	As defined in 5.3.11.3.9.
ChannelIndex	Integer	0x00–0x1f	As defined in 5.3.11.3.10.
HoppingSequenceLength	Integer	0x00–0xff	As defined in 5.3.11.3.4.
HoppingSequence	List of integers	0x0000–0x01ff for each channel	As defined in 5.3.11.3.5.

6.2.2.4 MLME-ASSOCIATE.confirm

Insert the following new parameters at the end of the list in 6.2.2.4 (before the closing parenthesis):

DSMEAssociationType,
AllocationOrder,
BIIndex,
SuperframeID,
SlotID,
ChannelIndex,
HoppingSequenceLength,
HoppingSequence

Insert the following new rows at the end of Table 12:

Table 12—MLME-ASSOCIATE.confirm parameters

Name	Type	Valid range	Description
DSMEAssociation Type	Integer	0x00–0x01	As defined in 5.3.11.2.2.
AllocationOrder	Integer	0x00–0x08	As defined in 5.3.11.3.6.
BIIndex	Integer	0x00–0xff	As defined in 5.3.11.3.7.
SuperframeID	Integer	0x0000–0xffff	As defined in 5.3.11.3.8.
SlotID	Integer	0x00–0x0e	As defined in 5.3.11.3.9.
ChannelIndex	Integer	0x00–0x1f	As defined in 5.3.11.3.10.

Table 12—MLME-ASSOCIATE.confirm parameters

Name	Type	Valid range	Description
HoppingSequence Length	Integer	0x00–0xff	As defined in 5.3.11.3.4.
HoppingSequence	List of integers	0x0000–0x01ff for each channel	As defined in 5.3.11.3.5.

6.2.4 Communications notification primitives

6.2.4.1 MLME-BEACON-NOTIFY.indication

Insert the following new row at the end of Table 17:

Table 17—Elements of PANDescriptor

Name	Type	Valid range	Description
TRLE Descriptor	TRLE Descriptor value	As defined in S.5.1.1	The TRLE Descriptor for the received beacon.

6.2.21 Primitives for DSME

6.2.21.1 Primitives for DSME-GTS management

6.2.21.1.1 MLME-DSME-GTS.request

Insert the following new parameter at the end of the list in 6.2.21.1.1 (before the closing parenthesis):

AllocationOrder

Insert the following new row at the end of Table 44q:

Table 44q—MLME-DSME-GTS.request parameters

Name	Type	Valid range	Description
AllocationOrder	Integer	0x00–0x08	As defined in 5.3.11.3.6.

6.2.21.1.2 MLME-DSME-GTS.indication

Insert the following new parameter at the end of the list in 6.2.21.1.2 (before the closing parenthesis):

AllocationOrder

Insert the following new row at the end of Table 44r:

Table 44r—MLME-DSME-GTS.indication parameters

Name	Type	Valid range	Description
AllocationOrder	Integer	0x00–0x08	As defined in 5.3.11.3.6.

6.2.21.1.3 MLME-DSME-GTS.response

Insert the following new parameters at the end of the list in 6.2.21.1.3 (before the closing parenthesis):

AllocationOrder
BIIndex,
SuperframeID,
SlotID,
ChannelIndex

Insert the following new rows at the end of Table 44s:

Table 44s—MLME-DSME-GTS.response parameters

Name	Type	Valid range	Description
AllocationOrder	Integer	0x00–0x08	As defined in 5.3.11.3.6.
BIIndex	Integer	0x00–0xff	As defined in 5.3.11.3.7
SuperframeID	Integer	0x0000–0xffff	As defined in 5.3.11.3.8
SlotID	Integer	0x00–0x0e	As defined in 5.3.11.3.9
ChannelIndex	Integer	0x00–0x1f	As defined in 5.3.11.3.10.

6.2.21.1.4 MLME-DSME-GTS.confirm

Insert the following new parameters at the end of the list in 6.2.21.1.4 (before the closing parenthesis):

AllocationOrder
BIIndex,
SuperframeID,
SlotID,
ChannelIndex

Insert the following new rows at the end of Table 44t:

Table 44t—MLME-DSME-GTS.confirm parameters

Name	Type	Valid range	Description
AllocationOrder	Integer	0x00–0x08	As defined in 5.3.11.3.6.
BIIndex	Integer	0x00–0xff	As defined in 5.3.11.3.7
SuperframeID	Integer	0x0000–0xffff	As defined in 5.3.11.3.8
SlotID	Integer	0x00–0x0e	As defined in 5.3.11.3.9
ChannelIndex	Integer	0x00–0x1f	As defined in 5.3.11.3.10.

6.2.21.3.4 MLME-DSME-LINKSTATUSRPT message sequence charts

Insert the following new subclauses (6.2.22–6.2.22.3) after 6.2.21.3.4:

6.2.22 Operating parameter change primitives

These primitives support the coordination of a change in PHY operating parameters among peer devices.

6.2.22.1 MLME-PHY-OP-SWITCH.request

The MLME-PHY-OP-SWITCH.request primitive is used by a device to instruct a second device to switch PHY operating parameters, including channel, band, PHY type, or other parameters specific to a PHY.

The semantics of this primitive are:

```
MLME-PHY-OP-SWITCH.request    (
                              DeviceAddrMode,
                              DeviceAddr,
                              PHYParameterList,
                              TxIndirect,
                              TargetTime,
                              SignalMethod,
                              RepeatCount,
                              RepeatInterval,
                              SecurityLevel,
                              KeyIdMode,
                              KeySource,
                              KeyIndex
                              )
```

The primitive parameters are defined in Table 44aa.

Table 44aa—MLME-PHY-OP-SWITCH.request parameters

Name	Type	Valid range	Description
DeviceAddrMode	Enumeration	SHORT_ADDRESS, EXTENDED_ADDRESS	The addressing mode of the device being instructed to change its operating parameters.
DeviceAddr	Device address	As specified by the DeviceAddrMode parameter	The address of the device being instructed to change its operating parameters.
PHYParameterList	List of PHY PIB attributes and values	See 9.3	A list of the PHY PIB attribute names and values representing the PHY operating parameters to be changed.
TxIndirect	Boolean	TRUE, FALSE	When the TxIndirect parameter is set to TRUE, the multipurpose frame shall be sent using indirect transmission. When the parameter is set to FALSE, the multipurpose frame shall be sent using direct transmission.
TargetTime	Integer	$0–(2^{32}–1)$	The time, in microseconds, from the current time that the PHY operating parameter switch is to be carried out.
SignalMethod	Enumeration	USE_MP, USE_BEACON	The method to be used to signal intended switch.
RepeatCount	Integer	0–127	Number of times that the notification containing the PHY Parameter Change IE is repeated.
RepeatInterval	Integer	0–65535	The time, in microseconds, to delay between repeated transmissions.
SecurityLevel	Integer	As defined in Table 46	As defined in Table 46
KeyIdMode	Integer	As defined in Table 46	As defined in Table 46

Table 44aa—MLME-PHY-OP-SWITCH.request parameters *(continued)*

Name	Type	Valid range	Description
KeySource	Set of octets	As defined in Table 46	As defined in Table 46
KeyIndex	Integer	As defined in Table 46	As defined in Table 46

On receipt of the MLME-PHY-OP-SWITCH.request primitive, the MLME initiates the PHY parameter change notification procedure, as defined in 5.1.8a.

If the device is the PAN coordinator of a beacon-enabled PAN that is using enhanced beacons, and the SignalMethod parameter value is USE_BEACON, the method described in 5.1.8a.1 shall be initiated.

If the SignalMethod parameter value is USE_MP indicating the use of a multipurpose frame, the method described in 5.1.8a.2 shall be initiated. The RepeatInterval parameter value should be greater than the time required to complete a transmission, acknowledgement, and possible retransmissions.

6.2.22.2 MLME-PHY-OP-SWITCH.confirm

The MLME-PHY-OP-SWITCH.confirm primitive is used to inform the next higher layer of the initiating device whether the channel switching notification has completed successfully.

The semantics of this primitive are:

```
MLME-PHY-OP-SWITCH.confirm      (
                                status,
                                DeviceAddrMode,
                                DeviceAddress
                                )
```

The primitive parameters are defined in Table 44bb.

Table 44bb—MLME-PHY-OP-SWITCH.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	SUCCESS, TRANSACTION_OVERFLOW, TRANSACTION_EXPIRED, NO_ACK, CHANNEL_ACCESS_FAILURE, COUNTER_ERROR, FRAME_TOO_LONG, UNAVAILABLE_KEY, UNSUPPORTED_SECURITY, INVALID_PARAMETER, UNSUPPORTED_FEATURE	The status of the attempt to transmit the channel switching notification command.
DeviceAddrMode	Enumeration	SHORT_ADDRESS, EXTENDED_ADDRESS	The addressing mode given in the request primitive.
DeviceAddress	Device address	As specified by the DeviceAddrMode parameter	The address of the device given in the request primitive.

This primitive returns a status of either SUCCESS, if the PHY parameter change notification procedure has been completed, or the appropriate status parameter value indicating the reason for the request failure.

If the SignalMethod parameter in the request primitive is USE_BEACON and the device is a PAN coordinator in a beacon-enabled PAN that is not using enhanced beacon frames, the MLME-PHY-OP-SWITCH.confirm primitive shall return a status of UNSUPPORTED_FEATURE.

If the SignalMethod parameter in the request primitive is USE_BEACON and the device is not a PAN coordinator in a beacon-enabled PAN, the MLME-PHY-OP-SWITCH.confirm primitive shall return a status of INVALID_PARAMETER.

If the SignalMethod parameter value is USE_MP and the device does not support the use of multipurpose frames, the MLME-PHY-OP-SWITCH.confirm primitive shall return a status of UNSUPPORTED_FEATURE.

If the SignalMethod parameter value is USE_MP, the RepeatCount parameter value in the request primitive is greater than zero, and the RepeatInterval value is not greater than zero, the MLME-PHY-OP-SWITCH.confirm primitive shall return with a status of INVALID_PARAMETER.

6.2.22.3 MLME-PHY-OP-SWITCH.indication

The MLME-PHY-OP-SWITCH.indication primitive is used to indicate the reception of a multipurpose frame with a PHY Parameter Change IE and a Operating Mode Description IE. The PHY Parameters List contains the contents of the received PHY Parameter's IE. The TargetTime parameter contains the value of the Effective Time of Change field of the received PHY Parameter Change IE, the NotificationTime parameter contains the value of the Notification Time field of the received PHY Parameter Change IE, and the LocalTime parameter contains the local time reference value at the time of reception of the multipurpose frame containing the notification IEs.

The value of the remaining parameters are set according to the received frame, as described in 6.3.3.

The semantics of this primitive are:

```
MLME-PHY-OP-SWITCH.indication    (
                                 DeviceAddrMode,
                                 DeviceAddress,
                                 PHYParameterList,
                                 TargetTime,
                                 NotificationTime,
                                 LocalTime,
                                 SecurityLevel,
                                 KeyIdMode,
                                 KeySource,
                                 KeyIndex
                                 )
```

The primitive parameters are defined in Table 44cc.

Table 44cc—MLME-CHANNEL-SWITCH.indication parameters

Name	Type	Valid range	Description
DeviceAddrMode	Enumeration	SHORT_ADDRESS, EXTENDED_ADDRESS	The addressing mode of the device that transmitted the channel switch notification command. For a LECIM device, the default value is SHORT_ADDRESS.
DeviceAddress	Device address	As specified by the DeviceAddrMode parameter	The address of the device that transmitted the channel switch notification command.
PHYParameterList	List of PHY PIB attributes and values	See 9.3	A list of the PHY PIB attribute names and values representing the PHY operating parameters to be changed.
TargetTime	Integer	$0–(2^{32}–1)$	The time, in microseconds, from the current time that the PHY operating parameter switch is to be carried out.
NotificationTime	Integer	0–65535	Value of the Notification Time field of the received PHY Parameter Change IE.
LocalTime	Integer	Implementation-dependent	The time of reception of the multipurpose frame containing the IEs in the local device time reference.
SecurityLevel	Integer	As defined in Table 46	As defined in Table 46
KeyIdMode	Integer	As defined in Table 46	As defined in Table 46
KeySource	Set of octets	As defined in Table 46	As defined in Table 46
KeyIndex	Integer	As defined in Table 46	As defined in Table 46

6.3 MAC data service

6.3.1 MCPS-DATA.request

Insert the following new parameters at the end of the list in 6.3.1 (before the closing parenthesis):

IACKPolicy,
CriticalEventMessage

6.3.2 MCPS-DATA.confirm

Insert the following new rows at the end of Table 46:

Change Table 47 as indicated, and insert the following two new paragraphs at the end of 6.3.2:

If the MAC PIB attributes *macPriorityChannelAccess* or *macPCAAllocationSuperRate* are set differently from their respective conditions in Table 0.0a, or if the attribute *macPCAAllocationRate* does not satisfy the

Table 46—MCPS-DATA.request parameters

Name	Type	Valid range	Description
IACKPolicy	Integer	0x0000–0x0011	Specifies the I-ACK policy to be employed, as described in 5.2.4.25.4. This parameter is only used when MPDU fragmentation is enabled.
CriticalEventMessage	Boolean	TRUE, FALSE	A value of TRUE indicates that the message shall be processed as a critical event message, as described in 5.1.1.4.5. A value of FALSE indicates that the message is not a critical event message and shall be processed as described in 5.1.1.4.1.

Table 47—MCPS-DATA.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	SUCCESS, TRANSACTION_OVERFLOW, TRANSACTION_EXPIRED, CHANNEL_ACCESS_FAILURE, INVALID_ADDRESS, INVALID_GTS, NO_ACK, COUNTER_ERROR, FRAME_TOO_LONG, UNAVAILABLE_KEY, UNSUPPORTED_SECURITY, UNSUPPORTED_FEATURE, INVALID_PARAMETER, ACK_RCVD_NODSN_NOSA	The status of the last MSDU transmission.

minimum value defined by its respective condition in Table 0.0a, then the MAC sublayer may discard the PCA MSDU and set the status of the MCPS-DATA.confirm primitive to INVALID_PARAMETER.

If the MAC PIB attribute *macPriorityChannelAccess* is set to FALSE, the MAC sublayer will discard the PCA MSDU and the status of the MCPS-DATA.confirm primitive will be set to INVALID_PARAMETER.

6.4 MAC constants and PIB attributes

6.4.1 MAC constants

Change Table 51 (the entire table is not shown) as indicated:

6.4.2 MAC PIB attributes

The first paragraph of 6.4.2 is reproduced here to assist the reader in understanding the notation used in Table 52. No changes are made to this paragraph.

The MAC PIB comprises the attributes required to manage the MAC sublayer of a device. The attributes contained in the MAC PIB are presented in Table 52. Attributes marked with a dagger (†) are read-only attributes (i.e., attribute can only be set by the MAC sublayer), which can be read by the next higher layer using the MLME-GET.request primitive. All other attributes can be read or written by the next higher layer

Table 51—MAC sublayer constants

Constant	Description	Value
aMinCAPLength	The minimum number of symbols forming the CAP. This ensures that MAC commands can still be transferred to devices when GTSs are being used. An exception to this minimum shall be allowed for the accommodation of the temporary increase in the beacon frame length needed to perform GTS maintenance, as described in 5.2.2.1.3. See 5.1.1.4 for restrictions when PCA is enabled.	440

using the MLME-GET.request or MLME-SET.request primitives, respectively. Attributes marked with a diamond (◆) are optional for an RFD; attributes marked with an asterisk (*) are optional for both device types (i.e., RFD and FFD).

Insert the following new rows at the end of Table 52. The descriptions of macMaxBE, macMaxFrameTotalWaitTime, macMaxFrameRetries, and macMinBE are reproduced here to assist the reader. No changes are made to these descriptions.

Table 52—MAC PIB attributes

Attribute	Type	Range	Description	Default
macMaxBE	Integer	3–8	The maximum value of the backoff exponent, BE, in the CSMA-CA algorithm, as defined in 5.1.1.4.	5 except for LLDN mode = 3
macMaxFrameTotalWaitTime	Integer	As defined in 6.4.3	The maximum time to wait either for a frame intended as a response to a data request frame or for a broadcast frame following a beacon with the Frame Pending field set to one.	PHY dependent
macMaxFrameRetries	Integer	0–7	The maximum number of retries allowed after a transmission failure.	3
macMinBE	Integer	0–*macMaxBE*	The minimum value of the backoff exponent (BE) in the CSMA-CA algorithm, as described in 5.1.1.4.	3
macLECIMAlohaUnitBackoffPeriod	Integer	As defined in 5.1.1.4a	The number of symbols for backoff when PCA backoff algorithm is in use, as defined in 5.1.1.4a.	Implementation specific
macLECIMAlohaBE	Integer	0–*macMinBE*	The value of the constant backoff exponent for priority messages using CCA Mode 4 (ALOHA), as described in 5.1.1.4a.	*macMinBE*–1
macFragmentSize	Integer	PHY dependent	The number of octets in each fragment.	Implementation specific

Table 52—MAC PIB attributes *(continued)*

Attribute	Type	Range	Description	Default
macMPDUFragPadValue	Integer	0–255	The value used to pad out the last fragment when MPDU fragmentation is enabled.	Implementation specific
macMPDUFragmentationEnabled	Boolean	TRUE or FALSE	When TRUE, MPDU fragmentation is enabled. See 5.4. When FALSE, MPDU fragmentation is disabled.	FALSE
macMPDUFragSecure	Boolean	TRUE or FALSE	When set to TRUE, a MIC shall be used as the FVS, as described in 5.4.1.1. When set to FALSE, the FVS shall be calculated as in 5.4.1.2.	FALSE
macFragmentFrameCounter	Integer	0x00 0000–0x3FF FFFF	The outgoing MPDU counter to use when *macMPDUFragSecure* is TRUE. The counter is not used when *macMPDUFragSecure* is FALSE.	0x00 0000
macFragmentFVSType	Enumeration	16 or 32	The type of the FCS used for fragment validation. A value of 32 indicates a 4-octet FCS, as specified in 5.2.1.9. A value of 16 indicates a 2-octet FCS, as specified in 5.2.1.9. This attribute is only valid when MPDU fragmentation is implemented.	Implementation specific
macFVSoffset	Integer	0–127	Specifies the location of the FVS field within the PSDU of a fragment or I-ACK cell, as described in 5.2.4.25.8. NOTE— The upper range limit depends on the size of the PSDU that is supported by the PHY operating mode and should be set to a value less than [PSDU Size – Cell Overhead].	0
macFVSRIV	Set of octets	—	The nonzero RIV used for calculating the FVS field of fragment and I-ACK frames, see 5.2.4.25.8 and 5.2.1.9.	As defined in 5.2.1.9
macIACKprogressTimeout	Integer	Implementation specific	The duration, in modulated symbols, at which to generate an I-ACK when I-ACK policy 1 is in use.	Implementation specific
macPriorityChannelAccess	Boolean	TRUE or FALSE	Indicates whether PCA is enabled.A value of TRUE indicates that it is enabled, while a value of FALSE indicates that it is disabled.	FALSE

Table 52—MAC PIB attributes *(continued)*

Attribute	Type	Range	Description	Default
macPCAAllocationSuperRate	Boolean	TRUE or FALSE	Indicates the PCA allocation rate per superframe. A value of TRUE indicates one or more allocations per superframe. A value of FALSE indicates less than one allocation per superframe.	TRUE
macPCAAllocationRate	Integer	Minimum rate defined in 5.1.1.4.5; maximum rate is 255.	The PCA allocation rate. If *macPCAAllocationSuperRate* is TRUE, the value is the number of allocations per superframe. If *macPCAAllocationSuperRate* is FALSE, the value is the number of superframes per PCA allocation.	1
macCritMsgDelayTol	Integer	0–60	The maximum interval between two consecutive PCAs, in milliseconds.	4

6.4.3 Calculating PHY dependent MAC PIB values

6.4.3.2 General MAC PIB attributes for functional organization

Change the first paragraph of 6.4.3.2 as indicated:

Table 52a provides the General MAC PIB attributes for functional organization. Attributes marked with a dagger (†) are read-only attributes (i.e., attribute can only be set by the MAC sublayer), which can be read by the next higher layer using the MLME-GET.request primitive. All other attributes can be read or written by the next higher layer using the MLME-GET.request or MLME-SET.request primitives, respectively.

Insert the following new rows at the end of Table 52a:

Table 52a—General MAC PIB attributes for functional organization

Attribute	Type	Range	Description	Default
macExtendedDSME capable†	Boolean	TRUE, FALSE	A value of TRUE indicates that the device is capable of functionality specific to ExtendedDSME. A value of FALSE indicates that the device is not capable of functionality specific to ExtendedDSME.	Implementation specific
macExtendedDSME enabled	Boolean	TRUE, FALSE	A value of TRUE indicates that the device is using functionality specific to ExtendedDSME. A value of FALSE indicates that the device is not using functionality specific to ExtendedDSME.	FALSE
macLEHSenabled	Boolean	TRUE, FALSE	A value of TRUE indicates that the device is using functionality specific to low energy hand shake. A value of FALSE indicates that the lew energy handshake is not used.	Implementation specific

Table 52a—General MAC PIB attributes for functional organization *(continued)*

Attribute	Type	Range	Description	Default
macRelayingMode	Boolean	TRUE, FALSE	Indication of whether the MAC sublayer is in a relaying mode. A value of TRUE indicates that the MAC sublayer only accepts frames that satisfy the relaying mode filtering requirements. A value of FALSE indicates that the MAC sublayer accepts frames that satisfy the filtering requirements described in 5.1.6.2.	Implementation specific
macTRLEenabled	Boolean	TRUE, FALSE	If TRUE, the device is using functionality specific to TRLE. If FALSE, the device is not operating as a TRLE PAN.	Implementation specific

6.4.3.4 MAC PIB attributes for hopping sequence

Change Table 52f (the entire table is not shown) as indicated:

Table 52f—MAC PIB attributes for Hopping Sequence

Attribute	Type	Range	Description	Default
macHoppingSequenceID	Integer	0x00–0x0f	~~Each~~ <u>The unique ID of the</u> hopping sequence ~~has a unique ID~~.	0

6.4.3.6 DSME-specific MAC PIB attributes

Change Table 52h (the entire table is not shown) as indicated. Insert the new rows at the end of the table. The description of the attribute macDSMEACT is reproduced here to assist the reader. No change is made to this description.

Table 52h—DSME-specific MAC PIB attributes

Attribute	Type	Range	Description	Default
macChannelDiversityMode	Integer	0–1	Indicates the method of channel diversity: 0x00 = Channel Adaptation 0x01 = Channel Hopping This value is not valid for a nonbeacon-enabled PAN.	~~0x00~~ 0
macMultisuperframeOrder	Integer	0–~~15~~<u>22</u>	The length of a multi-superframe<u>,</u> which is a cycle of the repeated superframes.	15
macDSMEACT	Bitmap	Refer to Table 1a	The allocation counter table of the DSME-GTS allocated to the device.	0
<u>*macAllocationOrder*</u>	<u>Integer</u>	<u>0–8</u>	<u>As defined in 5.3.11.3.6. If MO ≤ BO, the value shall be set to zero.</u>	<u>0</u>

Table 52h—DSME-specific MAC PIB attributes *(continued)*

Attribute	Type	Range	Description	Default
macBIIndex	Integer	0–255	As defined in 5.3.11.3.7.	0
macDSMEAssociationType	Integer	0–1	Indicates whether DSME-GTSs are allocated during the association procedure. This attribute is set to one if a device requests assignment of a DSME-GTS during association. Otherwise, it is set to zero.	1

Insert the following new rows at the end of Table 52i:

Table 52i—Elements of Neighbor Information

Attribute	Type	Range	Description
AllocationOrder	Integer	0–8	As defined in 5.3.11.3.6.
AssociationType	Integer	0–1	Indicates whether DSME-GTSs are allocated during the association procedure. This element shall be set to one if DSME-GTSs are allocated during association. Otherwise, it shall be set to zero.

6.4.3.7 LE-specific MAC PIB attributes

Insert the following new rows at the end of Table 52j. The description of macLowEnergySuperframeSupported is reproduced here to assist the reader. No change is made to this description.

Table 52j—LE-specific MAC PIB attributes

Attribute	Type	Range	Description	Default
macLowEnergySuperframe Supported	Boolean	TRUE or FALSE	Indication of whether the low-energy superframe is operational or not. If this attribute is TRUE, the coordinator shall not transmit beacon frames regardless of BO value. This attribute shall be set to FALSE if the device is aware of the existence of allocated GTS.	Implementation specific
macCSLInterval	Integer	*macMaxFrame TotalWaitTime*–65535	Specifies the interval between two successive CSL wake-up frames in the wakeup sequence, in units of 10 symbols.	*macMaxFrame TotalWaitTime*

Table 52j—LE-specific MAC PIB attributes *(continued)*

Attribute	Type	Range	Description	Default
macIRITOffsetInterval	Integer	0x0000–0xffff	A value of zero indicates that I-RIT is disabled. A nonzero value specifies the interval, in symbol periods, from the end of the transmitted frame to the beginning of the I-RIT listening period.	0x00
macIRITListenDuration	Integer	0x00–0xff	The duration of listening time, in symbol periods, for which the receiver is listening for the beginning of a frame to receive.	0x64
macIRITEnabled	Boolean	TRUE, FALSE	If TRUE, the IRIT mode of operation is enabled, as described in 5.1.11.3. If FALSE, the IRIT mode of operation is disabled.	FALSE

8. General PHY requirements

8.1 General requirements and definitions

Insert the following items at the end of the second list in 8.1:

— **LECIM DSSS PHY:** a multi-regional, direct sequence spread spectrum (DSSS) PHY operating with characteristics that enable support of LECIM applications, as defined in 19.1.

— **LECIM FSK PHY:** a multi-regional, frequency shift keying (FSK) PHY operating with characteristics that enable support of LECIM applications, as defined in 19.2.

8.1.1 Operating frequency range

Change the first paragraph of 8.1.1 as indicated, and insert two new tables (Table 66a and Table 66b):

A compliant device shall operate in one or several frequency bands ~~using the modulation and spreading formats~~ summarized in Table 66, Table 66a, and Table 66b. Table 66a shows frequency bands for devices supporting the LECIM DSSS PHY, and Table 66b shows frequency bands for devices supporting the LECIM FSK PHY.

Table 66a—Operating frequency ranges for LECIM DSSS PHY

Band identifier	Frequency range (MHz)	Bandwidth (kHz)	Modulation	Chip rate (kchips/s)
470	470–510	100	BPSK	100
			O-QPSK	200
780	779–787	1000	BPSK	1000
			O-QPSK	2000
863	863–870	100	BPSK	100
			O-QPSK	200
915	902–928	200	BPSK	200
			O-QPSK	400
		400	BPSK	400
			O-QPSK	800
		600	BPSK	600
			O-QPSK	1200
		800	BPSK	800
			O-QPSK	1600
		1000	BPSK	1000
			O-QPSK	2000

Table 66a—Operating frequency ranges for LECIM DSSS PHY *(continued)*

Band identifier	Frequency range (MHz)	Bandwidth (kHz)	Modulation	Chip rate (kchips/s)
922	915–928	200	BPSK	200
			O-QPSK	400
		400	BPSK	400
			O-QPSK	800
		600	BPSK	600
			O-QPSK	1200
		800	BPSK	800
			O-QPSK	1600
		1000	BPSK	1000
			O-QPSK	2000
917	917.1–923.5	200	BPSK	200
			O-QPSK	400
		400	BPSK	400
			O-QPSK	800
		600	BPSK	600
			O-QPSK	1200
		800	BPSK	800
			O-QPSK	1600
		1000	BPSK	1000
			O-QPSK	2000
920	920–928	200	BPSK	200
			O-QPSK	400
		400	BPSK	400
			O-QPSK	800
		600	BPSK	600
			O-QPSK	1200
		800	BPSK	800
			O-QPSK	1600
		1000	BPSK	1000
			O-QPSK	2000

Table 66a—Operating frequency ranges for LECIM DSSS PHY *(continued)*

Band identifier	Frequency range (MHz)	Bandwidth (kHz)	Modulation	Chip rate (kchips/s)
921	921–928	200	BPSK	200
			O-QPSK	400
		400	BPSK	400
			O-QPSK	800
		600	BPSK	600
			O-QPSK	1200
		800	BPSK	800
			O-QPSK	1600
		1000	BPSK	1000
			O-QPSK	2000
2450	2400–2483.5	1000	BPSK	1000
			O-QPSK	2000

Table 66b—Operating frequency ranges for LECIM FSK PHY

Band identifier	Frequency range (MHz)	Bandwidth (kHz)	Modulation	Bit rate (kbits/s)
169	169.400–169.475	25	FSK/GFSK/ P-FSK/P-GFSK	25
		12.5		12.5
433	433.050–434.790	37.5	FSK/GFSK/ P-FSK/P-GFSK	37.5
		25		25
		12.5		12.5
470	470–510	37.5	FSK/GFSK/ P-FSK/P-GFSK	37.5
		25		25
		12.5		12.5
780	779–787	37.5	FSK/GFSK/ P-FSK/P-GFSK	37.5
		25		25
		12.5		12.5
863	863–870	37.5	FSK/GFSK/ P-FSK/P-GFSK	37.5
		25		25
		12.5		12.5

Table 66b—Operating frequency ranges for LECIM FSK PHY

Band identifier	Frequency range (MHz)	Bandwidth (kHz)	Modulation	Bit rate (kbits/s)
915	902–928	37.5	FSK/GFSK/ P-FSK/P-GFSK	37.5
		25		25
		12.5		12.5
922	915–928	37.5	FSK/GFSK/ P-FSK/P-GFSK	37.5
		25		25
		12.5		12.5
917	917.1–923.5	37.5	FSK/GFSK/ P-FSK/P-GFSK	37.5
		25		25
		12.5		12.5
920	920–928	37.5	FSK/GFSK/ P-FSK/P-GFSK	37.5
		25		25
		12.5		12.5
921	921–928	37.5	FSK/GFSK/ P-FSK/P-GFSK	37.5
		25		25
		12.5		12.5

8.1.2 Channel assignments

8.1.2.1 Channel numbering for 780 MHz band

Change the first paragraph of 8.1.2.1 as indicated:

This subclause does not apply to the SUN PHY or LECIM PHY specifications. ~~See 8.1.2.9 for an explanation~~ For explanations of channel numbering for the SUN PHYs and LECIM PHYs, see 8.1.2.9 and 8.1.2.12, respectively.

8.1.2.2 Channel numbering for 868 MHz, 915 MHz, and 2450 MHz bands

Change the first paragraph of 8.1.2.2 as indicated:

This subclause does not apply to the SUN PHY or LECIM PHY specifications. ~~See 8.1.2.9 for an explanation~~ For explanations of channel numbering for the SUN PHYs and LECIM PHYs, see 8.1.2.9 and 8.1.2.12, respectively.

8.1.2.3 Channel numbering for 950 MHz PHYs

Change the first paragraph of 8.1.2.3 as indicated:

This subclause does not apply to the SUN PHY or LECIM PHY specifications. ~~See 8.1.2.9 for an explanation~~ For explanations of channel numbering for the SUN PHYs and LECIM PHYs, see 8.1.2.9 and 8.1.2.12, respectively.

Insert the following new subclause (8.1.2.12–8.1.2.12.2) after 8.1.2.11:

8.1.2.12 Channel numbering for LECIM PHYs

A channel page (*phyCurrentPage;* 9.3) value of 12 indicates a LECIM PHY.

For the 2.4 GHz band, a device shall support all the channels from the lowest to the highest channels (inclusive) indicated in the LECIM Capabilities IE, as described in 5.2.4.28.

8.1.2.12.1 Channel numbering for LECIM DSSS PHY

When *phyCurrentLECIMPHYType* is set to DSSS, the channel plan is described as follows. The channel center frequency, *ChanCenterFreq*, for all LECIM DSSS PHY frequency bands shall be derived as follows:

$$ChanCenterFreq = FreqBandEdge + FreqOffset + (phyCurrentChannel - 1) \times ChanSpacing$$

where
ChanCenterFreq is the channel center frequency in MHz
FreqBandEdge is the band edge for the frequency band in use (*phyLECIMCurrentBand*), in MHz
FreqOffset is the frequency offset for each band in MHz
phyCurrentChannel is the designated channel identifier number from 1 to *N*
ChanSpacing is the separation between adjacent channels in MHz (*phyChannelSpacing*)

The parameters *FreqBandEdge*, *FreqOffset*, *ChanSpacing,* and the range of valid *phyCurrentChannel* channel numbers for each frequency band are listed in Table 68l.

Table 68l—Frequency band, frequency band offset, and channel spacing for LECIM DSSS PHY

Band identifier	*FreqBandEdge* (MHz)	*FreqOffset* (MHz)	*ChanSpacing* (MHz)	*phyCurrentChannel* range
433	433	0.17	0.1	1–16
	433	0.22	0.2	1–8
470	470	0.2	0.2	1–199
780	779	0.2	0.2	1–39
863	863	0.075	0.1	1–69
	863	0.125	0.2	1–34
915	902	0.2	0.2	1–129
917	917	0.1	0.2	1–32
920	920	0.6	0.2	1–36
921	921	0.2	0.2	1–34
922	915	0.2	0.2	1–64
2450	2400	0.2	0.2	1–416

8.1.2.12.2 Channel numbering for LECIM FSK PHY

When *phyCurrentLECIMPHYType* is set to FSK, the channel center frequency *ChanCenterFreq* for the LECIM FSK PHY shall be derived as follows:

$$ChanCenterFreq = ChanSpacing \times phyCurrentChannel + ChanCenterFreq_0 \quad (1)$$

where

ChanSpacing is the separation between adjacent channels in MHz (*phyChannelSpacing*)
phyCurrentChannel is the current channel number occurring in the range of 0 to *TotalNumChan*–1
TotalNumChan is the total number of channels for the available frequency band
$ChanCenterFreq_0$ is the first channel center frequency of the band in use (*phyLECIMCurrentBand*) in MHz

Parameters *TotalNumChan* and $ChanCenterFreq_0$ are specified in Table 68m and Table 68n for different frequency bands and channel spacings.

For band identifier 169, $ChanCenterFreq_0$ shall be 169.4375 MHz and *TotalNumChan* shall be one.

Table 68m—*TotalNumChan* and *ChanCenterFreq₀* when *ChanSpacing* = 200 kHz

Band identifier	*TotalNumChan*	$ChanCenterFreq_0$ (MHz)
433	8	433.22
470	199	470.2
780	39	779.2
863	34	863.125
915	129	902.2
917	32	917.1
920	36	920.6
921	34	921.2
922	64	915.2

Table 68n—*TotalNumChan* and $ChanCenterFreq_0$ when ChanSpacing = 100 kHz

Band identifier	*TotalNumChan*	$ChanCenterFreq_0$ (MHz)
433	16	433.170
470	399	470.1
780	79	779.1
863	69	863.075
915	259	902.1

Table 68n—*TotalNumChan* and *ChanCenterFreq*$_0$ when ChanSpacing = 100 kHz *(continued)*

Band identifier	*TotalNumChan*	*ChanCenterFreq*$_0$ (MHz)
921	69	921.1
922	129	915.1

8.1.7 Receiver sensitivity definitions

Change the first paragraph of 8.1.7 as indicated:

The conditions for measuring receiver sensitivity are defined in Table 69 with the exception of the LECIM DSSS PHY. Receiver sensitivity information for the LECIM DSSS PHY is given in 19.1.3.4.

8.2 General radio specifications

8.2.1 TX-to-RX turnaround time

Change the second paragraph of 8.2.1 as indicated:

The TX-to-RX turnaround time is defined as the time at the air interface from the trailing edge of the last part/chip (of the last symbol) of a transmitted PPDU to the time that the PHY is ready to receive the leading edge of the first part/chip (of the first symbol) of the next received PPDU.

8.2.2 RX-to-TX turnaround time

Change the second paragraph of 8.2.2 as indicated:

The RX-to-TX turnaround time is defined as the time at the air interface from the trailing edge of the last chip (of the last symbol) of a received PPDU to the time that the PHY is ready to transmit the leading edge of the first chip (of the first symbol) of the next transmitted PPDU.

9. PHY services

9.2 PHY constants

Change Table 70 (the entire table is not shown) as indicated:

Table 70—PHY constants

Constant	Description	Value
aMaxPHYPacketSize	The maximum PSDU size (in octets) the PHY shall be able to receive.	2047 for SUN and LECIM FSK PHYs. For LECIM DSSS PHY, this is not a constant; refer to *phyLECIMDSSSPSDUSize*. 127 for all other PHYs
aTurnaroundTime	RX-to-TX or TX-to-RX turnaround time (in symbol periods), as defined in 8.2.1 and 8.2.2.	For the SUN and LECIM FSK PHYs, the value is 1 ms expressed in symbol periods, rounded up to the next integer number of symbol periods using the ceiling() function.* For the LECIM DSSS PHY, the value is 1 ms expressed in modulation symbol periods, rounded up to the next integer number of symbol periods using the ceiling() function. The value is 12 for all other PHYs.

*The function ceiling() returns the smallest integer value greater than or equal to its argument value.

9.3 PHY PIB attributes

Insert the following new rows at the end of Table 71. The descriptions of phyCurrentChannel and phyCurrentPage are reproduced here to assist the reader. No changes are made to these descriptions.

Table 71—PHY PIB attributes

Attribute	Type	Range	Description
phyCurrentChannel	Integer	As defined in 8.1.2	The logical channel to use for all following transmissions and receptions, 8.1.2.
phyCurrentPage	Integer	Any valid channel page	This is the current PHY channel page. This is used in conjunction with *phyCurrentChannel* to uniquely identify the channel currently being used.
phyLECIMDSSSPPDUModulation	Enumeration	BPSK, O-QPSK	The selected modulation type. This attribute is only valid for the LECIM DSSS PHY.

Table 71—PHY PIB attributes *(continued)*

Attribute	Type	Range	Description
phyLECIMDSSSPPDUModulationRate	Enumeration	100, 200, 400, 600, 800, 1000, 2000	The modulation rate measured in modulation kilo symbols per second. This attribute is only valid for the LECIM DSSS PHY.
phyLECIMDSSSPPDUTxAt	Integer	0–[2^{32}–1]	The time, in modulation symbols, relative to the start of the beacon. This attribute is only valid for the LECIM DSSS PHY.
phyLECIMDSSSPSDUSpreadingFactor	Integer	16–32 768	2^x (where x = 4–15) chips per symbol. This attribute is only valid for the LECIM DSSS PHY.
phyLECIMDSSSPSDUGoldCodeSeed	Integer	0–[2^{25}–1]	The seed for the Gold code generator when encoding the PSDU. This attribute is only valid for the LECIM DSSS PHY.
phyLECIMDSSSPSDUGoldCodeResetPerSymbol	Boolean	TRUE or FALSE	Reset Gold code generator per symbol. This attribute is only valid for the LECIM DSSS PHY.
phyLECIMDSSSPSDUSize	Enumeration	16, 24, 32	The size, in octets, of the PSDU. This attribute is only valid for the LECIM DSSS PHY.
phyLECIMDSSSSHRSpreadingFactor	Integer	16–32 768	2^x (where x = 4–15) chips per symbol. This attribute is only valid for the LECIM DSSS PHY.
phyLECIMDSSSSHRGoldCodeSeed	Integer	0–[2^{25}–1]	The seed for the Gold code generator when encoding the SHR. This attribute is only valid for the LECIM DSSS PHY.
phyLECIMDSSSSHRGoldCodeResetPerSymbol	Boolean	TRUE or FALSE	Reset Gold code generator per symbol. This attribute is only valid for the LECIM DSSS PHY.
phyLECIMDSSSPreambleSize	Enumeration	0, 16, 32	The length of the preamble, as stated in Figure 154. This attribute is only valid for the LECIM DSSS PHY.
phyLECIMDSSSSFDPresent	Boolean	TRUE or FALSE	A value of TRUE indicates that the SFD is present. A value of FALSE indicates that the SFD is not present. This attribute is only valid for the LECIM DSSS PHY.

Table 71—PHY PIB attributes *(continued)*

Attribute	Type	Range	Description
phyLECIMFECTailBitingEnabled	Boolean	TRUE or FALSE	A value of TRUE indicates that tail biting is enabled. A value of FALSE indicates that it is disabled. This attribute is only valid for the LECIM DSSS PHY.
phyLECIMDSSSPSDUOVSF-SpreadingFactor	Integer	1–256	The length of the generated code in power of 2. A value of 1 indicates that OVSF is not enabled. This attribute is only valid for the LECIM DSSS PHY.
phyLECIMDSSSPSDUOVSF-CodeIndex	Integer	0, 1, ..., *N*–1	Specifies the desired code from the available set of codes. The value of *N* is given by *phyLECIMDSSSPSDUOVSFSpreadingFactor*. This attribute is only valid for the LECIM DSSS PHY.
phyLECIMFSKPreambleLength	Integer	4–64	The number of times the preamble contains the pattern defined in 19.2.1.1. This attribute is only valid for the LECIM FSK PHY.
phyLECIMFSKPSDUPositionMod	Boolean	TRUE or FALSE	Indicates whether position-based modulation is enabled. A value of TRUE indicates that position-based modulation is enabled. A value of FALSE indicates that it is not enabled. This attribute is only valid for the LECIM FSK PHY.
phyLECIMFSKSpreading	Boolean	TRUE or FALSE	A value of TRUE indicates that spreading is enabled. A value of FALSE indicates that spreading is disabled. This attribute is only valid for the LECIM FSK PHY.
phyLECIMFSKSpreadingFactor	Enumeration	1, 2, 4, 8, 16	The spreading factor (SF) to be used when *phyLECIMFSKSpreading* is TRUE. This attribute is only valid for the LECIM FSK PHY.
phyLECIMFSKSpreadingPattern	Enumeration	ALTERNATING_1/0, NON_ALTERNATING	Specifies the type of pattern used for spreading when spreading is enabled. This attribute is only valid for the LECIM FSK PHY.

Table 71—PHY PIB attributes *(continued)*

Attribute	Type	Range	Description
phyLECIMFSKScramblePSDU	Boolean	TRUE or FALSE	A value of FALSE indicates that data whitening of the PSDU is disabled. A value of TRUE indicates that data whitening of the PSDU is enabled. This attribute is only valid for the LECIM FSK PHY.
phyLECIMFECEnabled	Boolean	TRUE or FALSE	A value of TRUE indicates that FEC is turned on. A value of FALSE indicates that FEC is turned off. This attribute is only valid for the LECIM FSK PHY.
phyLECIMFSKInterleavingEnabled	Boolean	TRUE or FALSE	A value of TRUE indicates that interleaving is turned on. A value of FALSE indicates that interleaving is turned off. This attribute is only valid for the LECIM FSK PHY.
phyLECIMCurrentBand	Enumeration	169, 433, 470, 780, 863, 915, 917, 920, 921, 922, 2450	The operating frequency band currently selected.
phyLECIMFSKSymbolRate	Float	See Table 66b	The currently selected symbol rate in *k*-symbols per second. The valid symbol rates per band are given in Table 66b.
phyCurrentLECIMPHYType	Enumeration	DSSS, FSK	Specifies the LECIM PHY type in use.
phyChannelSpacing	Enumeration	100, 200	The channel spacing, measured in kHz, that is used with *phyCurrentBand* and *phyCurrentChannel* to specify the frequency channel being used.

9.4 PHY PIB attribute values for *phyMaxFrameDuration* and *phySHRDuration*

Change the first paragraph of 9.4 as shown:

For PHYs other than CSS, UWB, the LECIM PHYs, and the SUN PHYs, the attribute *phyMaxFrameDuration* is given by:

Insert the following new paragraphs at the end of 9.4:

For the LECIM DSSS PHY, the attribute *phyMaxFrameDuration* is given by:

$$phyMaxFrameDuration = phySHRDuration + phyPSDUDuration$$

If the SHR is present, the symbol rate is defined as the bit rate of the SHR. The attributes *phySHRDuration* and *phyPSDUDuration* are defined as follows:

$$phySHRDuration = phyLECIMDSSSPreambleSize + M$$

where M represents the SFD length in bits. If *phyLECIMDSSSSFDPresent* is TRUE, then $M = 8$; otherwise, $M = 0$.

$$phyPSDUDuration = \text{ceiling}\left[\frac{(phyLECIMDSSSPSDUSize + N) \times 2 \times 8 \times phyLECIMDSSSPSDUSpreadingFactor}{phyLECIMDSSSSHRSpreadingFactor}\right]$$

where N represents the number of pad octets having a value of all zeros. If *phyLECIMFECTailBitingEnabled* is FALSE, then $N = 1$; otherwise, $N = 0$.

For the LECIM DSSS PHY, if the SHR is not present, the symbol rate is defined as the symbol rate of the PSDU. In this case, the attributes *phySHRDuration* and *phyPSDUDuration* are defined as follows:

$$phySHRDuration = 0 \text{ and } phyPSDUDuration = (phyLECIMDSSSPSDUSize + N) \times 2 \times 8$$

where N represents the number of pad octets having a value of all zeros. If *phyLECIMFECTailBitingEnabled* is FALSE, then $N = 1$; otherwise, $N = 0$.

For the LECIM FSK PHY, the attribute *phyMaxFrameDuration* is given by:

$$phyMaxFrameDuration = (phyLECIMFSKPreambleLength + 3 + 2 + aMaxPHYPacketSize) \times phySymbolsPerOctet$$

Insert after Clause 18 the following new clause (Clause 19):

19. LECIM PHYs

Two PHYs are specified in order to support LECIM applications: DSSS, as described in 19.1, and FSK, as described in 19.2.

19.1 DSSS PHY specification

The DSSS PHY is described in the following subclauses.

19.1.1 PPDU format for DSSS

For convenience, the PPDU structure for this PHY is presented so that the leftmost field as written in this standard shall be transmitted first. All multiple octet fields shall be transmitted least significant octet first, and each octet shall be transmitted least significant bit (LSB) first.

The PSDU field carries the data of the PPDU. The size of the field is set by the value of *phyLECIMDSSSPSDUSize*. The composition of the PSDU field is affected by the optional use of tail biting, as described in 19.1.2.3. The PPDU shall be formatted as illustrated in Figure 154.

Octets		
0/2/4	**0/1**	**16/24/32**
Preamble	SFD	PSDU
SHR		PHY payload

Figure 154—Format of the LECIM DSSS PPDU

The SHR, if present, is used for obtaining frequency, symbol, and frame synchronization. It consists of the preamble and the SFD. It is possible to recover a fixed length frame without the use of an SFD or SHR.

The Preamble field, if present, is used to obtain symbol timing and frequency offset. A preamble length of 0, 2, or 4 octets may be commissioned via *phyLECIMDSSSPreambleSize*. The 2 and 4 octet preambles are given in Table 189.

Table 189—LECIM DSSS preamble and SFD values

phyLECIMDSSSPreambleSize	**Preamble field**	**SFD field (if *phyLECIMDSSSSFDPresent* is TRUE)**
0	Not present	Not present
16	0011 1111 0101 1001	0011 1000
32	0000 1111 1101 1011 0110 0111 0010 1010	1000 0100

The SFD field, if present, indicates the beginning of the frame. One SFD is used when the preamble length is 2 octets, and a second SFD is used when the preamble length is 4 octets. Both SFDs are given in Table 189.

19.1.2 Modulation and spreading

In this subclause, modulation symbol refers to the output of the BPSK/O-QPSK modulator, as shown in Figure 155.

19.1.2.1 Data rate

The information data rate depends on the band in use, the spreading factor, the modulation rate, and the modulation being used, and it is calculated as follows:

$$\text{DataRate} = 0.5 \times \frac{(phyLECIMDSSSPPDUModulationRate \times ChipPerSymbol)}{phyLECIMDSSSPSDUSpreadingFactor} \text{ kbps}$$

where *ChipPerSymbol* = 1 when BPSK modulation is used and *ChipPerSymbol* = 2 when O-QPSK modulation is used. The term 0.5 represents the FEC ½ coding.

19.1.2.2 Reference modulator diagram

The functional block diagram in Figure 155 is provided as a reference for specifying the LECIM DSSS PHY modulation. All binary data contained in the SHR and PSDU shall be encoded using the modulation shown in Figure 155.

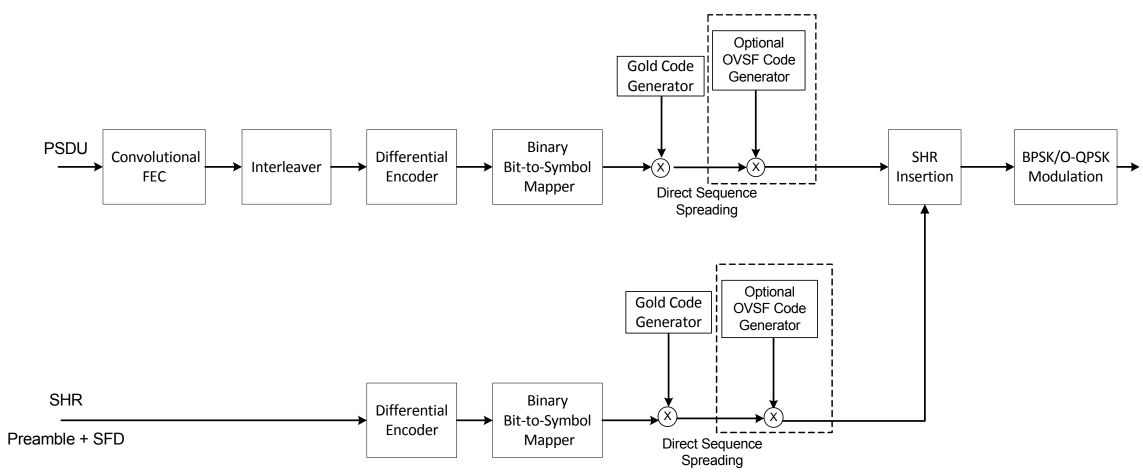


Figure 155—LECIM DSSS reference modulator diagram

19.1.2.3 Convolutional forward error correction (FEC) encoding

FEC shall employ rate 1/2 convolutional coding with constraint length $k = 7$ using the following generator polynomials:

$$G_0(x) = 1 + x^2 + x^3 + x^5 + x^6$$

$$G_1(x) = 1 + x + x^2 + x^3 + x^6$$

The encoder is shown in Figure 156, where $\oplus$ denotes modulo-2 addition.

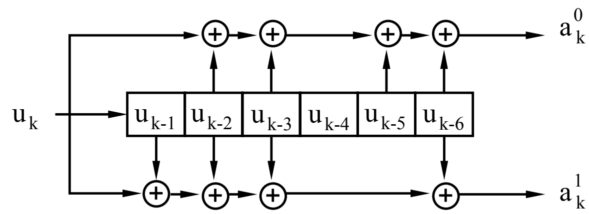


Figure 156—LECIM DSSS PHY convolutional encoder

Tail biting may optionally be employed. When *phyLECIMFECTailBitingEnabled* is set to TRUE, the possible sizes of the PSDU are as defined in Figure 154 and the initial encoder state at $k = 0$ shall be set to the last six bits of the PSDU.

When *phyLECIMFECTailBitingEnabled* is set to FALSE, the initial encoder state at $k = 0$ shall be set to $(u_{-1}, u_{-2}, \ldots, u_{-6}) = (0, 0, 0, 0, 0, 0)$. The size of the PSDU is reduced by one octet, and the PSDU shall be extended to equal one of the possible sizes defined in Figure 154 by appending a termination sequence of eight bits, all zero.

19.1.2.4 Interleaver

The output of the convolutional encoder is interleaved using a pruned bit reversal interleaving algorithm.

The text that follows contains examples of bit reversal interleavers for three PSDU sizes (256, 384, and 512 bits). PSDU sizes that are not powers of two (e.g., 384) employ pruning.

19.1.2.4.1 256-bit fragment size

If the input sequence into the interleaver is represented by

$$[S_0\ S_1 \ldots S_{255}]$$

Then the output sequence of the interleaver can be described as

$$[S_0\ S_N\ \ldots\ S_{255}]$$

The value N for the M^{th} output is determined as the bit-reversal of the value M.

Representing the value M as a binary representation

$$M = [m_7\ m_6 \ldots m_0]$$

where m_i are the binary digits, then

$$N = [m_0\ m_1 \ldots m_7]$$

where M is incremented sequentially from 0 to 255.

For example if $M = 1 = 0000\ 0001_2$, then $N = 1000\ 0000_2 = 128$

19.1.2.4.2 384-bit fragment size

If the input sequence into the interleaver is represented by

$$[S_0\ S_{1\ldots}S_{383}] \tag{1}$$

Then the output sequence of the interleaver can be described as

$$[S_0\ S_N\ \ldots\ S_{383}]$$

The value *N* for the M_{th} output is determined as the bit-reversal of the value *M*.

Representing the value *M* as a binary representation

$$M = [m_8\ m_7\ldots m_0]$$

where m_i are the binary digits, then

$$N = [m_0\ m_1\ldots m_8]$$

where *M* is incremented sequentially from 0 to 511 and *M’* are the ordered set of *M* whose corresponding *N* is less than 384 (this is the pruning process).

For example:

- If $M = 1 = 00000\ 0001_2$, then $N = 10000\ 0000_2 = 256$.
- If $M = 2 = 00000\ 0010_2$, then $N = 01000\ 0000_2 = 128$.
- If $M = 3 = 00000\ 0011_2$, then $N = 11000\ 0000_2 = 384$, and since it is not less than 384, it would not be included in the ordered set *M’* (i.e., it is pruned from the result).
- If $M = 4 = 00000\ 0100_2$, then $N = 00100\ 0000_2 = 64$.

An example is given in Annex R.

19.1.2.4.3 512-bit fragment size

If the input sequence into the interleaver is represented by

$$[S_0\ S_1\ldots S_{511}]$$

Then the output sequence of the interleaver can be described as

$$[S_0\ S_N\ \ldots\ S_{511}]$$

The value *N* for the M^{th} output is determined as the bit-reversal of the value *M*.

Representing the value *M* as a binary representation

$$M = [m_8\ m_7\ldots m_0]$$

where m_i are the binary digits, then

$$N = [m_0\ m_1 \ldots m_8]$$

where M is incremented sequentially from 0 to 511.

For example if $M = 1 = 00000\ 0001_2$, then $N = 10000\ 0000_2 = 256$.

19.1.2.5 Differential encoding

The differential encoding of the DSSS PHY is described in 11.2.3.

19.1.2.6 Bit-to-symbol and symbol-to-chip encoding

Each input bit shall be mapped to a binary symbol using the mapping:

$$x[n] = \begin{cases} 1, & \text{if } b[n] = 0 \\ -1, & \text{if } b[n] = 1 \end{cases}$$

These binary symbols shall be spread to chip-rate with spreading factor (SF). This process is illustrated in Figure 157 for SF = 8. The symbols are first up-sampled SF times and interpolated using a scaled boxcar filter, as shown in Figure 158, i.e., the symbol is repeated SF times at chip-rate. Note that this is a mathematical representation of the direct sequence spreading operation. This process can be implemented in an alternative manner that is mathematically equivalent. The up-sampled symbols are multiplied by a specified Gold code to create the spread signal.

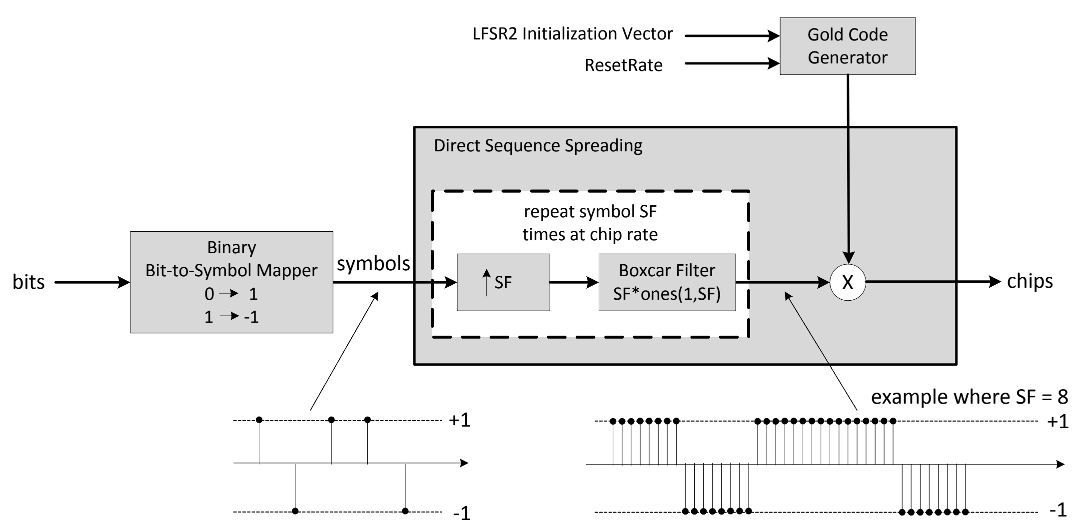


Figure 157—Bit-to-chip diagram for LECIM DSSS PHY

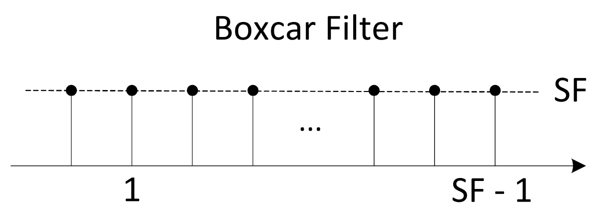


Figure 158—Boxcar filter

19.1.2.6.1 Gold code generator

Gold code sequences are a large family of easily parameterized PN sequences with good periodic cross-correlation and off-peak auto-correlation properties. A Gold code sequence is derived from the binary addition (XOR) of two maximum length sequences (*m*-sequences, or MLS). The *m*-sequences are generated using Fibonacci linear feedback shift registers (LFSR). Each LFSR is constructed from primitive (or prime) polynomials over Galois field 2 (GF[2]). The resulting sequences thus constitute segments of a set of Gold sequences. The Gold sequence can be parameterized by setting the initialization vector of LFSR2 to different values (LFSR1 is always initialized to 0x1).

- — $m = 25$ (length of LFSR)
- — $n = 2^m - 1 = 33{,}554{,}431$ (length of Gold code)
- — $n + 2 = 33{,}554{,}433$ (total Gold sequences) = $a, b, a \times b, a \times Tb, a \times T2b, \ldots$

LFSR (MLS) generator polynomials:

- — $p1(x) = x^{25} + x^3 + 1$
- — $p2(x) = x^{25} + x^3 + x^2 + x + 1$

19.1.2.6.2 Orthogonal variable spreading factor (OVSF) code generator

The OVSF code is the same as the Walsh code, except that each sequence has a different index number in the code set, which results from their different generator algorithms.

In a LECIM system, a Gold code shall be used inside a co-located orthogonal network (CLON) as the primary code. An OVSF code is optionally used to identify the CLONs and clusters in order to provide double protection from outside interference.

The OVSF code is defined recursively by a tree structure, as shown in Figure 159.

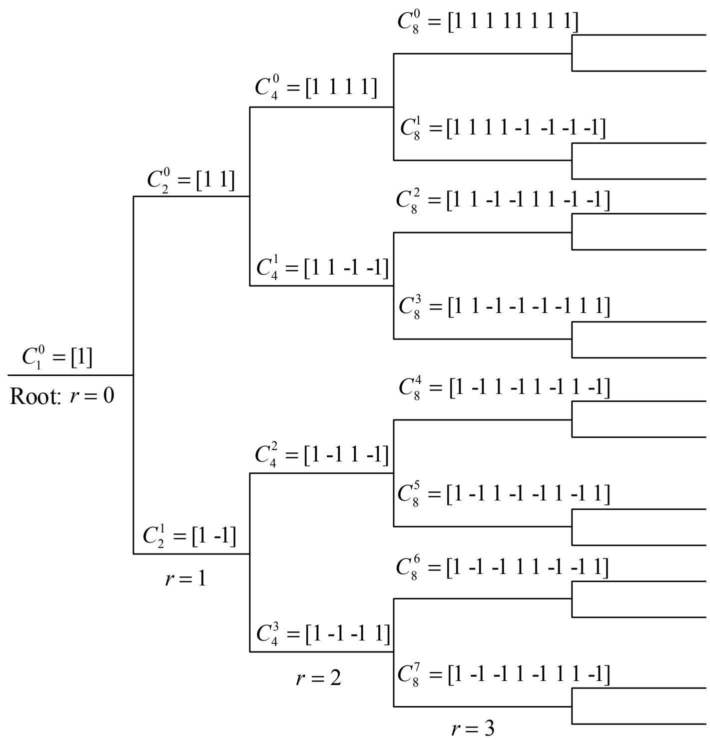


Figure 159—OVSF code tree

The OVSF code generator block outputs may be specified by two parameters in the mask of the block: the SF and the code index. In Figure 159, $C_N^{\,i}$ is a code of length $N = 2^r$ at depth r in the tree. The code index i has the range $\{0, 1, \ldots, N-1\}$, which specifies how far down the column of the tree at depth r the code appears. The root code $C_1^{\,0}$ has length $N = 1$, code index $i = 0$, and depth $r = 0$. Two branches of length 2^{r+1} leading out of $C^i{}_N$ are labeled by the sequences $[C^i{}_N\ C^i{}_N]$ and $[C^i{}_N\ \overline{C}^i{}_N]$, where $\overline{C}^i{}_N = -C_N^{\,i}$.

To recover the code from the SF and the code index, the following procedure is applied. Convert the code index i into binary form. If $i < N-1$, add zeros to the left side of this binary code index in order to make it have the N-bits form. To choose the specific code in the tree, the path is determined using the binary path sequence of the form $x = [x_1, x_2, \ldots, x_r]$. This binary path sequence describes the path from the root to the specific code, according to the following rule: the path takes the upper branch from the code at depth r' if $x_{r'} = 0$, or the lower branch if $x_{r'} = 1$ for $1 \le r' \le r$. For example, with the root $C_i^{\,0} = [1]$ and $r = \log_2 N$ of $C^i{}_N$, then $C_{2N}^{\,2i}$ and $C_{2N}^{\,2i+1}$ are defined as:

$$C_{2N}^{\,2i} = [C^i{}_N\ C^i{}_N] \text{ if } x_{r+1} = 0 \text{ and } C_{2N}^{\,2i+1} = [C^i{}_N\ \overline{C}^i{}_N] \text{ if } x_{r+1} = 1.$$

To make the just described procedure more clear, a specific example is given. Assuming the code has SF $N = 16$ and code index $i = 6$, the steps are as follows:

a) Convert $i = 6$ to the binary number 110.

b) Add one 0 to the left to obtain 0110, which has length $r = \log_2 16 = 4$.

c) Construct the sequences $C_N^{\,i}$ according to Table 190.

From Table 190, code ${C_{16}}^6$ has SF $N = 16$ and code index $i = 6$.

Table 190—Example of OVSF code recovery

Path depth r	Path sequence x_r	Code index i	Code C_N^i
0		0	$C_1^0 = [1]$
1	0	0	$C_2^0 = [C_1^0\ C_1^0] = [1][1]$
2	1	1	$C_4^1 = [C_2^0\ \overline{C}_2^0] = [1\ \ 1][-1\ -1]$
3	1	3	$C_8^3 = [C_4^1\ \overline{C}_4^1] = [1\ \ 1\ -1\ \ -1][-1\ -1\ \ 1\ \ 1]$
4	0	6	$C_{16}^6 = [C_8^3\ C_8^3] = [1\ \ 1\ -1\ \ -1\ \ -1\ \ -1\ \ 1\ \ 1][1\ \ 1\ -1\ \ -1\ \ -1\ \ -1\ \ 1\ \ 1]$

The logical level architecture of the OVSF code generator is shown in Figure 160. There are two inputs for the OVSF code generator: an OVSF code index i and SF N. The code index i is stored in the N-bit binary representation as $(V_{N-1}V_{N-2}\ldots V_1V_0)$. According to the input SF N, the chip rate binary counter counts incrementally from 0 to $N - 1$ in the N-bit binary representation as $(b_{N-1}b_{N-2}\ldots b_1b_0)$.

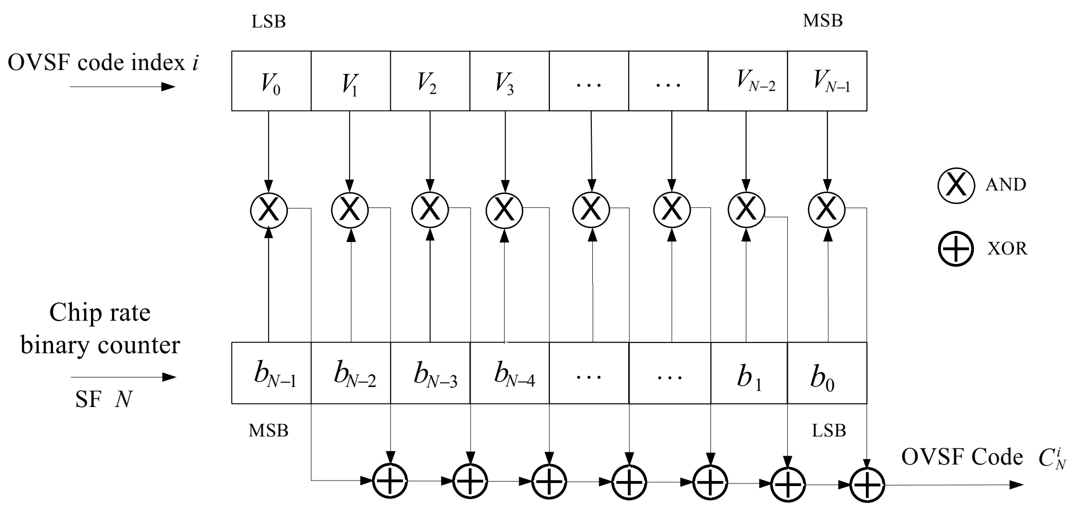


Figure 160—Logical level architecture of OVSF code generator for LECIM DSSS PHY

For example, to generate the code ${C_8}^5$ in Figure 159, considering the digital CMOS logic operation, the mapping {"+1" → "logic 0"} and {"–1" → "logic 1"} is specified. The participation of the specific bits in the XOR operation according to the OVSF code index i is periodic in time and can be controlled by the chip rate binary counter, as illustrated in Figure 161 and Table 191.

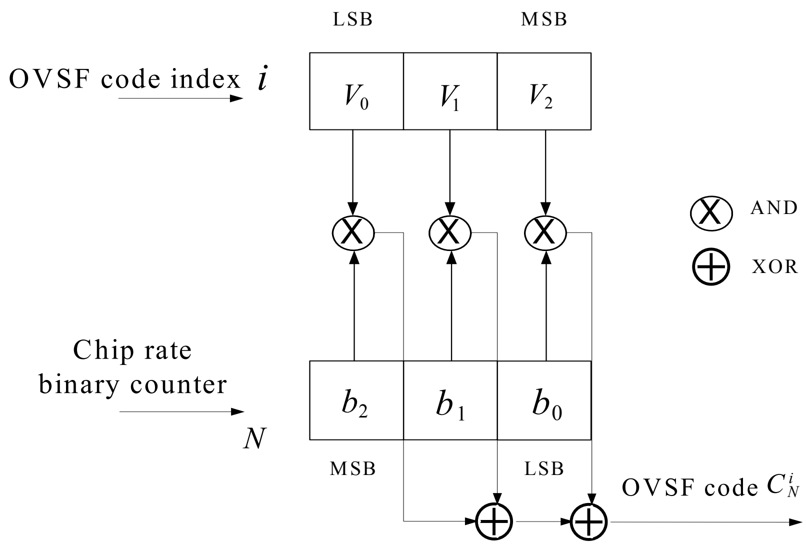


Figure 161—An example of OVSF code generator for LECIM DSSS PHY

Table 191—Example of OVSF code output

Chip rate counter $b_2\ b_1\ b_0$	Operation $V_0\ V_1\ V_2$ with code index $i = 5$	OVSF code output C^5_8	
		CMOS logic mapping form	Form in Figure 159
0 0 0	0	0	1
0 0 1	V_2	1	–1
0 1 0	V_1	0	1
0 1 1	$V_1 \oplus V_2$	1	–1
1 0 0	V_0	1	–1
1 0 1	$V_0 \oplus V_2$	0	1
1 1 0	$V_0 \oplus V_1$	1	–1
1 1 1	$V_0 \oplus V_1 \oplus V_2$	0	1

The PIB attributes *phyLECIMDSSSPSDUOVSFSpreadingFactor* and *phyLECIMDSSSPSDUOVSFCodeIndex* specify the OVSF code output. The same values shall be used to recover the OVSF code.

19.1.2.7 BPSK/O-QPSK modulation

19.1.2.7.1 BPSK modulation

Binary phase-shift keying (BPSK) modulation for the DSSS PHY is described in 11.2.5.

The chip sequences are modulated onto the carrier using BPSK with pulse shaping. A chip value of one corresponds to a positive pulse and a chip value of zero corresponds to a negative pulse.

Chip rates/bands are shown in Table 66a.

During each symbol period, chip C_0 is transmitted first and C_{SF-1} is transmitted last.

19.1.2.7.2 O-QPSK modulation

The chip sequences representing each data symbol are modulated onto the carrier using offset quadrature phase-shift keying (O-QPSK). Even-indexed chips are modulated onto the in-phase (I) carrier, and odd-indexed chips are modulated onto the quadrature-phase (Q) carrier. To form the offset between I-phase and Q-phase chip modulation, the Q-phase chips shall be delayed by T_c with respect to the I-phase chips, as illustrated in Figure 162, where T_c is the inverse of the chip rate and SF is *phyLECIMDSSSPSDUSpreadingFactor*.

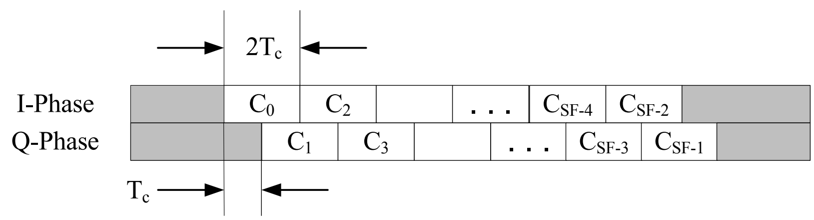


Figure 162—O-QPSK chip modulation

19.1.3 DSSS PHY RF requirements

19.1.3.1 Radio frequency tolerance

The DSSS PHY radio frequency tolerance shall be ±2.5 ppm.

19.1.3.2 Channel switch time

Channel switch time shall be less than or equal to 500 µs. The channel switch time is defined as the time elapsed at the antenna between the trailing edge of the last symbol of one PPDU to the leading edge of the first symbol of a consecutive PPDU sent on a different channel.

19.1.3.3 Transmit spectral mask

Implementers are responsible to assure that the transmit spectral content conforms to all local regulations.

19.1.3.4 Receiver sensitivity

The receiver sensitivity information is given in Table 192. The PER is $\leq 1\%$ for the following conditions: BPSK modulation, no tail biting, fragment length of 16 octets, a 2-octet preamble and an 8-bit SFD.

Table 192—Minimum LECIM DSSS PHY receiver sensitivity (dBm)

Spreading factor (chips/bit)	Modulation rate (ksym/s)				
	200	400	600	800	1000
16	–115	–112	–110	–109	–108
32	–118	–115	–113	–112	–111
64	–121	–118	–116	–115	–114
128	–124	–121	–119	–118	–117
256	–127	–124	–122	–121	–120
512	–130	–127	–125	–124	–123
1024	–133	–130	–128	–127	–126
2048	–136	–133	–131	–130	–129
4096	–139	–136	–134	–133	–132
8192	–142	–139	–137	–136	–135
16384	–145	–142	–140	–139	–138
32768	–148	–145	–143	–142	–141

19.1.3.5 Receiver interference rejection

The minimum receiver interference rejection levels are given in Table 193. The adjacent channels are those on either side of the desired channel that are closest in frequency to the desired channel. The alternate channel is more than one removed from the desired channel in the operational frequency band.

Table 193—LECIM DSSS Minimum receiver interference rejection requirements

Adjacent channel rejection	Alternate channel rejection
10 dB	30 dB

The adjacent channels are:

$$ChanNum \pm (1 \times phyLECIMDSSSPPDUModulationRate / Spacing)$$

The variable *ChanNum* is the channel identifier number of the designated channel, *phyLECIMDSSSPPDUModulationRate* is defined in 9.3, and *Spacing* is $ChanSpacing \times 1000$ (*ChanSpacing* is defined in 8.1.2.12.1; conversion from MHz to kHz). The alternate channels are:

$$ChanNum \pm (2 \times phyLECIMDSSSPPDUModulationRate / Spacing)$$

19.1.3.6 TX-to-RX turnaround time

The DSSS PHY shall meet the requirements for TX-to-RX turnaround time, as defined in 8.2.1.

19.1.3.7 RX-to-TX turnaround time

The DSSS PHY shall meet the requirements for RX-to-TX turnaround time, as defined in 8.2.2.

19.1.3.8 Transmit power

A transmitter shall be capable of transmitting at least –3 dBm. The maximum transmit power is limited by local regulatory bodies.

19.2 FSK PHY specification

The FSK PHY is described in the following subclauses.

19.2.1 PPDU format for FSK

The FSK PPDU shall support the format shown in Figure 163.

The SHR, PHY header (PHR), and PHY payload components are treated as bit strings of length *n*, numbered b_0 on the left and b_{n-1} on the right. When transmitted, they are processed b_0 first to b_{n-1} last, without regard to their content or structure.

All reserved fields shall be set to zero upon transmission and shall be ignored upon reception.

Octets			
variable	**3**	**2**	**variable**
Preamble	SFD	As defined in 19.2.1.3	PSDU
SHR		PHR	PHY payload

Figure 163—Format of the LECIM FSK PPDU

19.2.1.1 Preamble field

The Preamble field shall contain *phyLECIMFSKPreambleLength* (as defined in 9.3) multiples of the 8-bit sequence “01010101.”

19.2.1.2 SFD

The SFD shall be a 3-octet sequence, as shown in Table 194.

The SFD is transmitted starting from the leftmost bit (i.e., starting with b_0).

19.2.1.3 PHR

The format of the PHR is shown in Figure 164. All multi-bit fields are unsigned integers and shall be processed MSB first.

Table 194—SFD value for LECIM FSK PHY

Octets	1	2	3
Bit map	0111 0000	1110 1110	1101 0010

The Frame Length field specifies the total number of octets contained in the PSDU (prior to FEC encoding, if enabled). The most significant bit (leftmost) shall be transmitted first.

The FCS Type field specifies the length of the FCS field, as defined in 5.2.1.9. A value of zero indicates a 4-octet FCS field, and a value of one indicates a 2-octet FCS field.

The Parity field in Figure 164 is defined in the following way:

$$\text{Parity} = \text{FCS} \oplus \text{DW} \oplus R_1 \oplus R_0 \oplus L_{10} \oplus L_9 \oplus L_8 \oplus L_7 \oplus L_6 \oplus L_5 \oplus L_4 \oplus L_3 \oplus L_2 \oplus L_1 \oplus L_0$$

Bit string index	0–1	2	3	4	5–15
Bit mapping	R_1–R_0	Parity	FCS	DW	L_{10}–L_0
Field name	Reserved	Parity	FCS Type	Data Whitening	Frame Length

Figure 164—PHR for 2047 octet packet

19.2.1.4 PSDU field

The PSDU field carries the data of the PPDU.

19.2.2 Modulation and coding for FSK

The modulation for the FSK PHY shall be FSK/Gaussian FSK (GFSK) or position-based FSK (P-FSK)/ position-based GFSK (P-GFSK).

In the 169 MHz band, the modulation index shall be:

— 0.5 for 25 kb/s
— 1.0 for 12.5 kb/s.

For all other LECIM FSK PHY band identifiers, the modulation index shall be:

— 0.5 for 37.5 kb/s
— 1.0 for 25 kb/s
— 2.0 for 12.5 kb/s

Either 100 kHz or 200 kHz channel spacing may be used as permitted by local regulations.

The FSK symbol timing used for the MAC and PHY timing parameters shall be:

$$\frac{1}{phyLECIMFSKSymbolRate} \text{ ms}$$

The use of P-FSK/P-GFSK modulation for PSDU data is controlled by the PIB attribute *phyLECIMFSKPSDUPositionMod*, as defined in 9.3. The modulation for preamble, SFD, and PHR shall be FSK/GFSK regardless of the value of *phyLECIMFSKPSDUPositionMod*.

FSK/GFSK encodes one bit by transmitting a frequency modulated signal $m(t)$ with duration T_S, i.e., $0 \le t < T_S$. P-FSK/P-GFSK encodes two bits by transmitting a FSK/GFSK modulated signal $m(t)$ with T_s duration in one of two possible positions (also known as time deviation), i.e., $0 \le t < T_S$ and $T_S \le t < 2T_S$.

19.2.2.1 Reference modulator diagram

The functional block diagram in Figure 165 is provided as a reference for specifying the FSK PHY data flow processing functions. The subclause number in each block refers to the subclause that describes that function. Each bit shall be processed using the bit order rules defined in 19.2.1.

When FEC is enabled, the PHR and PSDU shall be processed for coding, as described in 19.2.2.4. When data whitening is enabled, the scrambling shall be only applied over the PSDU, as described in 19.2.3. When spreading is enabled, the spreading shall be applied over the PHR and PSDU, as described in 19.2.2.6.

All fields in the PPDU shall use the same symbol rate and modulation order, unless otherwise specified elsewhere in this standard.

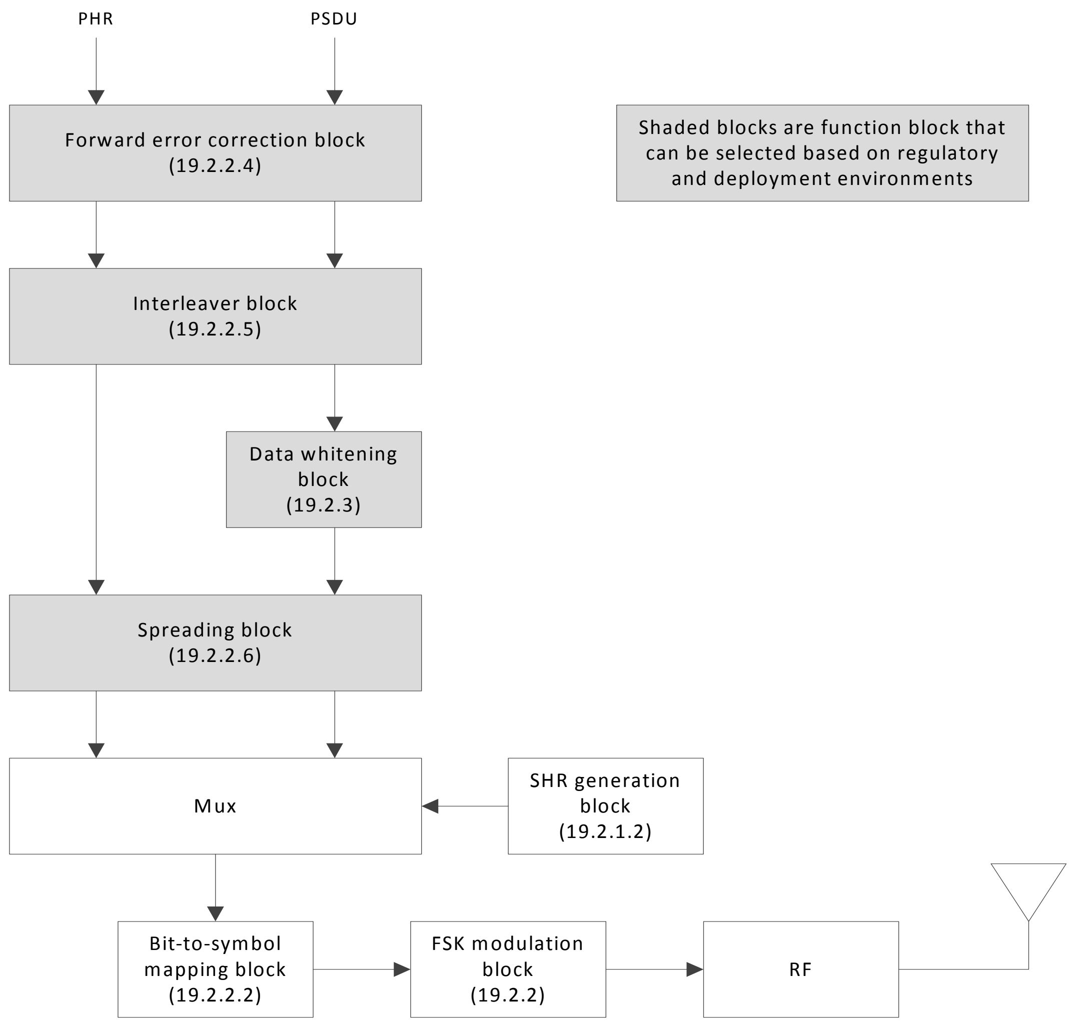


Figure 165—LECIM FSK reference modulator diagram

19.2.2.2 Bit-to-symbol mapping

The nominal frequency deviation, f_{dev}, shall be

$$\frac{(\text{symbol rate} \times \text{modulation index})}{2}$$

The symbol encoding for FSK/GFSK and P-FSK/GFSK modulation is shown in Table 195 and Table 196, respectively.

19.2.2.3 Modulation quality

Modulation quality shall be measured by observing the frequency deviation tolerance and the zero crossing tolerance of the eye diagram caused by a PN9 sequence of length 511 bits.

Table 195—FSK/GFSK symbol encoding

Symbol (b_0)	Frequency deviation	Time deviation
0	$-f_{dev}$	0
1	$+f_{dev}$	0

Table 196—P-FSK/P-GFSK symbol encoding

Symbol (b_0, b_1)	Frequency deviation	Time deviation
00	$-f_{dev}$	0
01	$-f_{dev}$	T_s
10	$+f_{dev}$	0
11	$+f_{dev}$	T_s

19.2.2.3.1 Frequency deviation tolerance

The frequency deviation tolerance shall be as given in 18.1.2.3.1 for 2-level modulation.

The symbol timing accuracy shall be better than ± 20 ppm.

19.2.2.3.2 Zero crossing tolerance

The excursions for the zero crossings for all trajectories of the eye diagram shall be constrained as specified in 18.1.2.3.2.

19.2.2.4 Forward error correction

The use of FEC is controlled by the PIB attribute *phyLECIMFECEnabled*, as defined in 9.3.

When used, FEC shall employ rate 1/2 convolutional coding with constraint length $K = 7$ using the following generator polynomials:

$$G_0(x) = 1 + x^2 + x^3 + x^5 + x^6$$

$$G_1(x) = 1 + x + x^2 + x^3 + x^6$$

The encoder is shown in Figure 166, where $\oplus$ denotes modulo-2 addition.

Prior to the convolutional encoding of the PHR bits, as described in 19.2.1.3, the initial encoder state at $k = 0$ shall be set to:

$$(u_{-1}, u_{-2}, \ldots, u_{-6}) = (0, 0, 0, 0, 0, 0)$$

and the sequence of PHR bits shall be extended by a termination sequence of six bits, all zero, as shown in Figure 167.

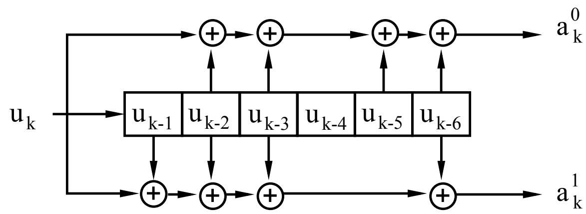


Figure 166—LECIM FSK PHY convolutional encoder

Prior to the convolutional encoding of the PSDU, the sequence of PSDU bits $b = \{b_0, b_1, \ldots, b_{8 \times \text{LENGTH} - 1}\}$, with its length (LENGTH) measured in octets, shall be extended by appending a termination sequence of six bits, all zero, and a sequence of additional bits (pad bits) as shown in Figure 167. The pad bits shall be set to zero and the number of pad bits, N_{PAD}, is computed from the number of blocks, N_B, the total number of uncoded bits, N_D, and the interleaver depth, N_{DEPTH}, as follows:

$$N_B = \text{ceiling}((8 \times \text{LENGTH} + 6)/(N_{\text{DEPTH}}/2)) \tag{2}$$

$$N_D = N_B \times (N_{\text{DEPTH}}/2) \tag{3}$$

$$N_{\text{PAD}} = N_D - (8 \times \text{LENGTH} + 6)$$

where the value of $N_{\text{DEPTH}} = N_{\text{PSDU}}$ is given in Table 197. The function ceiling(.) is a function that returns the smallest integer value greater than or equal to its argument value.

PHR bits	000000	PSDU bits	000000	pad bits

Figure 167—PHR and PSDU extension prior to encoding

The sequence shown in Figure 167 shall be passed to the convolutional encoder. The corresponding output sequence of code-bits, *z,* shall be generated as follows:

$$z = \{\ldots\ a_k^0, a_k^1, a_{k+1}^0, a_{k+1}^1, a_{k+2}^0, a_{k+2}^1\ \ldots\} = \{z_0, z_1, \ldots, z_{[2N_D + (N_{\text{DEPTH}} - 1)]}\}$$

i. e., a_k^0 is preceding sample a_k^1.The first sample, z_0, shall be passed to the interleaver first in time, and the last sample, $z_{[2N_D + (N_{\text{DEPTH}} - 1)]}$, shall be passed to the interleaver last in time. The value of $N_{\text{DEPTH}} = N_{\text{PHR}}$ is defined in Table 197.

19.2.2.5 Code-bit interleaving

The use of interleaving is controlled by the PIB attribute *phyLECIMFSKInterleavingEnabled*, as defined in 9.3.

Since the PHR bits are terminated, PHR code-bits and PSDU code-bits are independent code blocks. Interleaving of PHR code-bits is separate from the interleaving of the PSDU code-bits.

Interleaving of code-bits shall be employed in conjunction with FEC. No code-bit interleaving shall be employed if FEC is not used.

The sequence of PHR code-bits consists of a single sequence

$$z^0 = \{z_0^0, \ldots, z_{N_{\mathrm{PHR}}-1}^0\}$$

of length N_{PHR}.

The sequence of PSDU code-bits consists of N_B subsequences

$$z^j = \{z_0^j, \ldots, z_{N_{\mathrm{PSDU}}-1}^j\} = \{z_{(j-1)N_{\mathrm{PSDU}}+N_{PHR}}, \ldots, z_{jN_{\mathrm{PSDU}}+N_{PHR}-1}\} \text{for } j = 1, \ldots, N_B$$

of length N_{PSDU}, with N_B described in Equation (2).

The interleaver is defined by a permutation. The index of the code-bits before the permutation shall be denoted by k, where $k = 0$ refers to the first sample, z_0^j, and $k = N_{\mathrm{DEPTH}} - 1$ refers to the last sample, $z_{N_{\mathrm{DEPTH}}-1}^j$, passed to the interleaver for a given subsequence z^j. The index i shall be the index after the permutation. The permutation is defined by the rule:

$$i = \frac{N_{\mathrm{DEPTH}}}{\lambda} \times ((N_{\mathrm{DEPTH}} - 1 - k) \bmod \lambda) + \mathrm{floor}\left(\frac{N_{\mathrm{DEPTH}} - 1 - k}{\lambda}\right) \quad k = 0, \ldots, N_{\mathrm{DEPTH}} - 1$$

where the degree λ is given in Table 197. The function floor(.) is a function that returns the largest integer value less than or equal to its argument value.

Table 197—Parameters of the interleaver

Field	Degree λ	Depth N_{DEPTH}
PHR	4	$N_{\mathrm{PHR}} = 4 \times 11 = 44$
PSDU	6	$N_{\mathrm{PSDU}} = 6 \times 12 = 72$

The process of interleaving a subsequence is shown in Figure 149. The first subsequence, z^0, shall be processed first in time and the last subsequence, z^{N_B}, shall be processed last in time.

The deinterleaver, which performs the inverse relation, is defined by the rule:

$$k = \lambda \times (N_{\mathrm{DEPTH}} - 1 - i) - (N_{\mathrm{DEPTH}} - 1) \times \mathrm{floor}\left(\frac{\lambda \times (N_{\mathrm{DEPTH}} - 1 - i)}{N_{\mathrm{DEPTH}}}\right) \quad i = 0, \ldots, N_{\mathrm{DEPTH}} - 1$$

19.2.2.6 Spreading

The use of spreading is controlled by the PIB attribute *phyLECIMFSKSpreading*, as defined in 9.3. The spreading factor (SF) can be 1, 2, 4, 8, or 16. The variable SF is indicated by the PIB attribute *phyLECIMFSKSpreadingFactor*, as defined in 9.3.

For spreading, a single input bit (b_0) is mapped into the spreading bits $(c_0, c_1, \ldots, c_{SF-1})$, as shown in Figure 168, and its mapping is represented in Table 198.

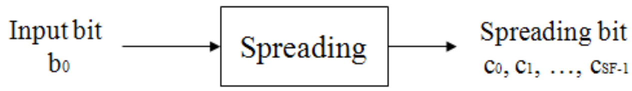


Figure 168—Spreading function

Table 198—Input bit to spreading bits mapping

phyLECIMFSK-SpreadingPattern	**Spreading factor (SF)**	**Input bit** $(b_0) = 0$	**Input bit** $(b_0) = 1$
ALTERNATING_1/0	2	$(c_0, c_1) = 01$	$(c_0, c_1) = 10$
ALTERNATING_1/0	4	$(c_0, \ldots, c_3) = 0101$	$(c_0, \ldots, c_3) = 1010$
ALTERNATING_1/0	8	$(c_0, \ldots, c_7) = 0101\ 0101$	$(c_0, \ldots, c_7) = 1010\ 1010$
ALTERNATING_1/0	16	$(c_0, \ldots, c_{15}) = 0101\ 0101\ 0101\ 0101$	$(c_0, \ldots, c_{15}) = 1010\ 1010\ 1010\ 1010$
NON_ALTERNATING	2	$(c_0, c_1) = 10$	$(c_0, c_1) = 01$
NON_ALTERNATING	4	$(c_0, \ldots, c_3) = 1010$	$(c_0, \ldots, c_3) = 0101$
NON_ALTERNATING	8	$(c_0, \ldots, c_7) = 1011\ 0001$	$(c_0, \ldots, c_7) = 0100\ 1110$
NON_ALTERNATING	16	$(c_0, \ldots, c_{15}) = 0010\ 0011\ 1101\ 0110$	$(c_0, \ldots, c_{15}) = 1101\ 1100\ 0010\ 1001$

19.2.3 Data whitening for FSK

Support for data whitening is optional.

The whitened data shall be the exclusive or (XOR) of the PSDU with the PN9 sequence, as described by the following equation:

$$E_\mathrm{n} = R_\mathrm{n} \oplus \mathrm{PN9}_\mathrm{n}$$

where

E_n is the whitened bit

R_n is the data bit being whitened

$\mathrm{PN9}_\mathrm{n}$ is the PN9 sequence bit

For each packet transmitted with data whitening enabled, R_0 is the first bit of the PSDU and the index n increments for subsequent bits of the PSDU.

For packets received with the Data Whitening field of the PHR set to one, the receiver decodes the scrambled data in the following way:

$$R_{\mathrm{n}} = RE_{\mathrm{n}} \oplus \mathrm{PN9}_{\mathrm{n}}$$

where

R_{n} is the PSDU bit after de-whitening

RE_{n} is the PSDU bit at the output of the filtered FSK demodulator

The PN generator is defined by the schematic in Figure 169.

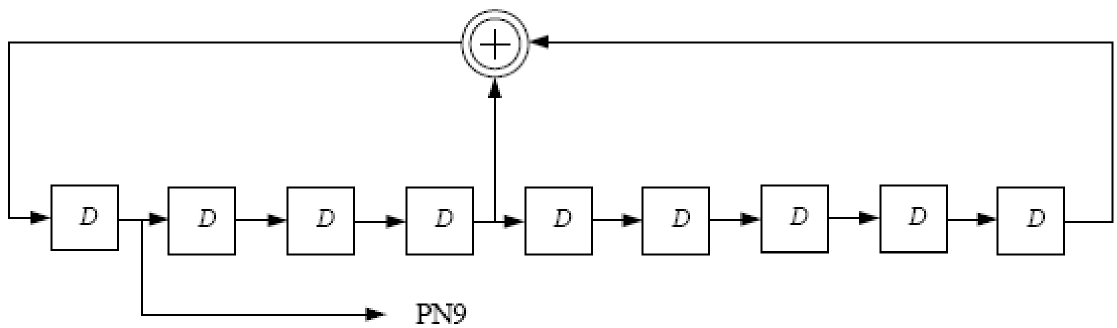


Figure 169—Schematic of the PN9 sequence generator

The seed in the PN9 generator shall be all ones: "111111111." The PN9 generator shall be reinitialized to the seed after each packet (either transmit or receive).

The PN9 generator is clocked using the seed as the starting point and enabled after the first clock cycle. For example, the first 30 bits out of the PN9 generator, once it is enabled, would be as follows:

$\mathrm{PN9}_{\mathrm{n}}$= 0_0, 0_1, 0_2, 0_3, 1_4, 1_5, 1_6, 1_7, 0_8, 1_9, 1_{10}, 1_{11}, 0_{12}, 0_{13}, 0_{14}, 0_{15}, 1_{16}, 0_{17}, 1_{18}, 1_{19}, 0_{20}, 0_{21}, 1_{22}, 1_{23}, 0_{24}, 1_{25}, 1_{26}, 0_{27}, 1_{28}, 1_{29}.

19.2.4 FSK PHY RF requirements

19.2.4.1 Operating frequency range

The FSK PHY operates in the bands given in 8.1.1.

19.2.4.2 Radio frequency tolerance

The clock radio frequency tolerance shall be within ±10 ppm .

19.2.4.3 Channel switch time

Channel switch time shall be less than or equal to 500 μs. The channel switch time is defined as the time elapsed at the antenna between the trailing edge of the last symbol of one PPDU to the leading edge of the first symbol of a consecutive PPDU sent on a different channel.

19.2.4.4 Transmit spectral mask

Implementers are responsible for ensuring that the transmit spectral content conforms to all local regulations.

19.2.4.5 Receiver sensitivity

Under the conditions specified in 8.1.7, a compliant device shall be capable of achieving a sensitivity of –97 dBm or better.

19.2.4.6 TX-to-RX turnaround time

The FSK PHY shall meet the requirements for TX-to-RX turnaround time as defined in 8.2.1.

19.2.4.7 RX-to-TX turnaround time

The FSK PHY shall meet the requirements for RX-to-TX turnaround time as defined in 8.2.2.

19.2.4.8 Transmit power

A compliant device shall be capable of transmitting with a power greater than or equal to –3 dBm. The maximum transmit power is limited by local regulatory bodies.

Annex A

(informative)

Bibliography

Insert the following new references alphanumerically in Annex A:

[B31] ETSI EN 300 220-1, Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD); Radio equipment to be used in the 25 MHz to 1 000 MHz frequency range with power levels ranging up to 500 mW; Part 1: Technical characteristics and test methods.

[B32] Public Law 107–56 (42 U.S.C. 5195c(e)), Section 1016(e), Critical Infrastructure Protection Act of 2001, October 2001.

Annex D

(informative)

Protocol implementation conformance statement (PICS) proforma[2]

Subclause D.2 is reproduced here to assist the reader in understanding the abbreviations and special symbols in this annex. No changes are made to D.2.

D.2 Abbreviations and special symbols

Notations for requirement status:

M Mandatory
O Optional
O.n Optional, but support of at least one of the group of options labeled O.n is required.
N/A Not applicable
X Prohibited
"item": Conditional, status dependent upon the support marked for the "item"

For example, FD1: O.1 indicates that the status is optional but at least one of the features described in FD1 and FD2 is required to be implemented, if this implementation is to follow the standard to which this PICS proforma is part.

D.7 PICS proforma tables

D.7.1 Functional device types

Insert new row to end of Table D.1 (the rest of the table is not shown) as indicated:

Table D.1—Functional device types

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
FD9	LECIM PHY device	8.1	O.3			

[2]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.

D.7.2 Major capabilities for the PHY

D.7.2.2 Radio frequency (RF)

Insert the following new rows at the end of Table D.3 (the rest of the table is not shown):

Table D.3—Radio frequency (RF)

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
RF17	LECIM PHYs					
RF17.1	LECIM DSSS	19.1	FD9: O.11			
RF17.2	LECIM FSK	19.2	FD9: O.11			
RF17.3	At least one of the bands given in Table 66a or Table 66b	8.1	FD9: M			
RF18	LECIM DSSS options					
RF18.1	LECIM DSSS convolutional FEC	19.1.2.3	RF17.1: M			
RF18.2	LECIM DSSS interleaver	19.1.2.4	RF17.1: M			
RF18.3	LECIM DSSS differential encoding	19.1.2.5	RF17.1:M			
RF18.4	LECIM DSSS bit-to-symbol and symbol-to-chip encoding	19.1.2.6	RF17.1: M			
RF18.5	LECIM DSSS BPSK modulation	19.1.2.7.1	RF17.1:O.12			
RF18.6	LECIM DSSS O-QPSK modulation	19.1.2.7.2	RF17.1:O.12			
RF19	LECIM FSK options					
RF19.1	LECIM FSK FEC	19.2.2.4	RF17.2: O			
RF19.2	LECIM FSK interleaving	19.2.2.5	RF17.2: O			
RF19.3	LECIM FSK spreading	19.2.2.6	RF17.2: O			
RF19.4	LECIM FSK data whitening	19.2.3	RF17.2: O			

Table D.3—Radio frequency (RF) *(continued)*

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
RF19.5	LECIM FSK One of the valid operating modes	19.2.2	RF17.2: M			
O.11 At least one of these features is supported. O.12 At least one of these features is supported.						

D.7.3 Major capabilities for the MAC sublayer

D.7.3.1 MAC sublayer functions

Change Table D.5 (the entire table is not shown) as indicated:

Table D.5—MAC sublayer functions

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
MLF17	DSME ~~C~~capability	6.2, Table 8c	O, MLF28:M			
MLF25	Fragmentation	5.4	O			
MLF26	Priority channel access (PCA)	5.1.1.4.5, 5.1.1.4a	O			
MLF27	Implicit receiver initiated transmission (I-RIT)	5.1.11.3				
MLF28	Extended DSME	5.1.10.1	O			
MLF29	Information elements	5.2.4	O, MLF25:M, MLF26:M, MLF28:M			
MLF30	Time-slot relaying based link extension (TRLE) capability	S.2	O			
MLF30.1	Link extension for non-TRLE PAN	S.3	MLF30:O.13			
MLF30.2	Link extension for TRLE-enabled PAN	S.4	MLF30:O.13			
MLF30.3	TRLE MAC management service	S.5.3	MLF30.1:M MLF30.2:M			
MLF30.4	TRLE command	S.5.2	MLF30.2:M			
O.13 At least one of these features is supported.						

Insert the following new annexes (Annex Q, Annex R, and Annex S) after Annex P:

Annex Q

(informative)

Low energy, critical infrastructure monitoring systems

Q.1 Introduction

Globally there are many definitions of critical infrastructure. For example, as per [B32], the term "critical infrastructure" means systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters. Most commonly associated with the term are facilities for:

- Electricity generation, transmission, and distribution
- Gas production, transport, and distribution
- Oil and oil products production, transport, and distribution
- Telecommunication
- Water supply (e.g., drinking water, waste water/sewage, stemming of surface water [e.g., dikes and sluices])
- Agriculture, food production, and distribution
- Heating (e.g., natural gas, fuel oil, district heating)
- Public health (e.g., hospitals, ambulances)
- Transportation systems (e.g., fuel supply, railway network, airports, harbors, inland shipping)
- Financial services (e.g., banking, clearing)
- Security services (e.g., police, military)

Q.1.1 LECIM characteristics

The LECIM portions of this standard form the MAC and PHY behaviors that implement a minimal network infrastructure, enables the collection of scheduled and event data from a large number of non-mains powered end points that are widely dispersed, or are in challenging propagation environments. To facilitate low energy operation necessary for multi-year battery life, MAC protocols minimize network maintenance traffic and device wake durations. In addition, LECIM addresses the changing propagation and interference environments encountered over many years.

The following is a list of LECIM characteristics and the underlying behaviors that form them:

a) Minimal infrastructure
   - Star topology, i.e., PAN coordinator communicates directly with devices.
   - Mains energy supply only for the PAN coordinator.
b) Commissioned network (not ad hoc)
   - PAN coordinators and devices are configured specifically for the deployed network.
   - PAN coordinators and devices are stateful, i.e., they are preconfigured with parameters that eliminate the need for wireless messages sending configuration information.

c) Long range
   — High receiver sensitivity, resulting from methods such as narrow bandwidth or high processing gain.
   — Interference robustness.
   — Challenging environments and widely dispersed devices.
d) Very limited energy supplied devices, such as:
   — Ten to twenty year battery life with no maintenance, i.e., original battery supplies all energy for the life of the device.
   — Energy harvesting with limited power supplies, i.e., short and infrequent transmission and reception durations.
e) Significant difference between PAN coordinator and devices
   — PAN coordinator may have significantly higher performance and a larger energy supply than the devices.
   — Does not preclude distributed systems.
f) Asymmetrical data flows
   — Sensor end point: up-link dominates data flow with limited down-link data needs.
   — Actuator end point: down-link dominates data flow with limited up-link data needs.

The following MAC enhancements are included to support the LECIM PHYs defined in Clause 19:

— Enhanced timing and synchronization capabilities to support synchronous and asynchronous channel access in both beacon-enabled and nonbeacon-enabled operation
— Enhanced low energy mechanisms
— MPDU fragmentation to support extremely low data rates and limited PSDU sizes
— PCA
— MLME-SAP and PIB extensions for PHY control and configuration

Q.1.2 Use case examples

The following use cases exemplify LECIM applications.

Q.1.2.1 Oil and gas pipeline monitoring

The key drivers of pipeline monitoring are as follows:

— Environmental protection
— Reliability (critical resources)
— Cost savings (increasing cost)
— Compliance (regulators)

Q.1.2.2 Water leak detection

The key drivers of water leak detection are as follows:

— Permanent installation of large number of sensors underground
— Long range and ability to penetrate underground vaults
— Battery operated and long lifetime
   — Small data messages once per day and in case of alarm event (e.g., leak detected)
— Low installation cost (easy deployment) and low cost of maintenance

Q.1.2.3 Soil monitoring

The key drivers of soil monitoring are as follows:

- Power consumption
  - Low-cost batteries that last over many years
- Networking
  - Long range links to cover large fields
  - Ability to use mesh or tree networking for complicated environment
  - Ability to connecting WPAN with mobile networks
- Reliability and cost
  - Very low maintenance requirements

Q.1.2.4 Inventory control - event driven with query

The application is for a warehouse floor with thousands of parts bins. Each bin has a battery operated RF link for communicating current quantity and changes in quantity to the central inventory control (CIC) system. Battery life is important.

Each bin contains only one part number. The RF link has an LCD display showing the quantity in the bin. It also has an “Increase Button” and a “Decrease Button.” When an operator adds units to the bin, he presses the Increase Button, and when parts are removed, he presses the Decrease Button. Each time a button is pressed, it generates an event to the RF module, which then transmits the change to the CIC. This would most likely use a contention access method for transmission, since events occur in an unscheduled manner.

The CIC receives events from all of the bins, as changes are made to the quantity contained in each bin. Both the local RF module and the CIC maintain the quantity in the bin.

For inventory auditing, it is necessary for the CIC to query each bin to check the quantity. This requires the CIC to initiate a transaction with each bin, either individually or as a broadcast/multicast message. The desire is to have all bins report within a reasonable time (minutes).

Also, since changes in quantity are event driven, the CIC needs a means to query each bin to make sure that it is still operational and that no “change in quantity” events were missed.

To minimize battery drain, the LECIM device is only activated when necessary:

- A change in quantity as indicated by a button event
- Some type of synchronous sniff/query operation for receiving queries from the CIC
- A response to query messages

Q.1.2.5 Building monitoring - time and event driven data with query

A building (or any structure) is being monitored by sensors that report measurement or state information over long periods, e.g., several minutes to several hours. There may also be sensors that report events or changes in state that are event driven and not time driven. Battery life is important.

Each measurement sensor is set to report its information at a certain interval, using either a GTS or the CAP. This gives very low duty cycle for normal operation, which is 99% of the usage. There may also be sensors that are event driven and report change in state, such as door open/closed, door locked/unlocked, switch on/off, etc. This is also low duty cycle.

Occasionally there is an event, such as an emergency, where the central monitoring system requires readings from all sensors as soon as possible. The central controller sends a request to all sensors to report their current measurement or state. This requires a low latency response mechanism capable of maintaining long battery life.

Q.1.3 LECIM behaviors

The following assumptions and precepts are essential to address the needs of LECIM applications:

- Commissioning
- Low energy
- Coverage extension

Q.1.3.1 Commissioning

Commissioning by a professional installer allows the network to reduce the amount of data to be sent by creating statefulness. The commissioning parameters are not expected to change over the duration of the network.

The following is one, simple example of commissioning to enable communication among three LECIM DSSS devices (devices *A*, *B*, and *C*), where device *A* is a powered coordinator and devices *B* and *C* are end devices.

PHY PIB attributes (commissioned):

Modulation-related PIB attributes

- *phyLECIMDSSSPPDUModulation* = O-QPSK
- *phyLECIMDSSSPPDUModulationRate* = 1000

SHR-related PIB attributes

- *phyLECIMDSSSPreambleSize* = 16
- *phyLECIMDSSSSHRGoldCodeResetPerSymbol* = TRUE
- *phyLECIMDSSSSHRGoldCodeSeed*
- *phyLECIMDSSSSHRSpreadingFactor*

PSDU-related PIB attributes

- *phyLECIMDSSSPSDUSize* = 32
- *phyLECIMDSSSPSDUGoldCodeResetPerSymbol* = FALSE
- *phyLECIMDSSSPSDUGoldCodeSeed*
- *phyLECIMDSSSPSDUSpreadingFactor*

The PIB attribute *phyCurrentChannel*, the Gold code seed value, and the spreading factor value need to be shared among communicating parties but do not necessarily need to be the same for each direction in a link. For example, if three devices (A,B,C) make up a star network where device A acts as the PAN coordinator, device A may use one set of code/spreading for its beacon transmission and use two additional, unique codes/spreading for reception from devices B and C. This ability to use different codes, or logical channels, provides a mechanism to address hidden node problems and interference from other co-located networks. For example, two nodes hidden from each other may have overlapping transmissions that can successfully be decoded by a receiver, provided the receiver has the ability to simultaneously demodulate two or more different sets of PN sequences at the same time (e.g., additional processing resources, CDMA). This ability eliminates the need for the end devices to re-transmit hidden node collisions, thus saving energy and improving system capacity.

For the purposes of this example, the frequency band is set to 902 MHz. When the transmitter is device A, and the receivers are devices B and C, the values of *phyCurrentChannel*, the Gold code seed, and the spreading factor are (5, 0x0123, 7). When the transmitter is device B and the receiver is device A, the set of values is (5, 0x0789, 7). When the transmitter is device C and the receiver is device A, the set of values is (5, 0x0def, 7).

Q.1.3.2 Low energy

LECIM applications require significantly low energy operation, in order to be able to either last 20 years on the original battery supply or on energy harvesting mechanisms. Achieving low energy operation is made very difficult given the low data rates necessary for long range operation. Accordingly, LECIM networks should be capable of eliding any overhead octets not absolutely necessary in order to minimize transmit and receive durations, schedule link times to minimize device “on” durations, and maximize link reliability to minimize retransmissions.

The maximum PPDU size that a LECIM PHY is able to receive is 2047 octets. To facilitate the multi-year battery life operation expected for envisaged LECIM applications, and given the low over the air (OTA) chip rate provisioned by the PHY in terms of allowable spreading factor (32,768 chips per symbol for the DSSS PHY and 16 chips per symbol in the case of the FSK PHY), it is recommended that small PPDU sizes be used.

As an example, the on-air time for an unfragmented 2047 octet frame at a symbol rate of 12.5 kb/s will require a minimum of 1.3 seconds total air time to be transmitted or received. If that same frame has a spreading factor of eight applied to each symbol, the OTA broadcast time will exceed 10 seconds. This increase in transmission and reception time will have a significant impact upon the battery longevity of a LECIM device, even allowing for low duty cycle operation. It should also be noted that the increased transmission time may lead to regulatory duty cycle limitations, especially in the case of the PAN coordinator.

Q.1.3.3 Coverage extension

To keep infrastructure costs to a minimum, LECIM devices have large link margins to achieve long ranges without requiring mesh devices or repeater devices. Requiring a mesh topology would increase the number of devices needed to sustain the network and, in most cases, require mains power for these devices. To extend the coverage for supporting sparse dispersed devices beyond the link margin or to maintain connections in dramatically changing environments, optional frame relaying repeaters located between the concentrator and devices are included in this standard to sustain the connections without reconfiguring the whole LECIM network.

Q.1.3.4 Device sensitivity and interference robustness

To support long range operations, the LECIM device is intended to have high receiver sensitivity and interference robustness. The high receiver sensitivity (capable of supporting 120 dB path losses) is achieved via low data rates, FEC, high processing gains, and other such mechanisms. The interference rejection specification for the LECIM device needs to support the criticality aspect of infrastructure monitoring such as co-channel rejection, improved receiver interference rejection, and blocking immunity. Attention is drawn to the class two receiver requirements of European standard ETSI EN 300 220-1 [B31] as an example of typical receiver immunity requirements for a LECIM device.

Q.2 Functionality added

The following functions have been added to this standard in order to implement LECIM applications: DSSS, FSK, fragmentation, frame priority, TRLE, PIB attributes, and IEs.

Q.2.1 DSSS

The DSSS devices used by LECIM networks differ from the other DSSS devices defined in this standard in that they have significant processing gain to allow devices to receive messages with very low or negative carrier-to-noise ratios. High processing gain also allows for CDMA operation to reduce the possibility of collisions.

With high spreading factors and CDMA, transmitted signals from other devices within radio range of the receiver that are operating on different codes are likely to be undetectable, because they may fall below the effective noise floor. This should be taken into account when configuring the CCA mode to be used; however, in many applications, sensing of the medium is not practical or useful, so selecting the CCA mode for use with the CSMA algorithm that equates to CCA Mode 4 (ALOHA) is recommended.

There are a great many options available in LECIM DSSS PHY that provide the ability to best address the applications throughout a diverse and changing set of regulatory environments. Some options may not be valid in some regulatory regimes, and it is up to the OEM and/or higher layers to specify options which comply with local regulations.

For example, under the current FCC regulations it would be perfectly legal to use a *phyLECIMDSSSPPDUModulationRate* of 400 (kHz), with certain restrictions. Specifically, the device would be required to use frequency hopping and would need to limit transmission to ≤ 400 ms. A *phyLECIMDSSSPSDUSize* of 32 octets, after FEC, yields a minimum of 512 modulation symbols per fragment. Using BPSK modulation, at a spreading factor of 2^8 (256), the fragment duration would be 328 ms.

Higher spreading factors would not be allowed under FCC rules. Under other regulatory domains at this modulation rate, frequency hopping is not required and the maximum duration (and spreading factor) may not be limited to 256 (≤ 400 ms).

Q.2.2 FSK

The LECIM FSK PHY uses a transmit signal characterized by a constant envelope, which allows for low cost implementation and good transmit power efficiency.

LECIM FSK devices are typically narrow bandwidth (hence low data rate) to permit higher sensitivity and an increased number of channels in each band, which can reduce the probability of packet collision.

Features, such as forward error correction, with a relatively high constraint length and robust interleaving, as well as spreading capability, are included to allow for further sensitivity gains.

Q.2.3 Fragmentation

With the addition of very low data rate PHY operating modes, the resulting increase in the over-the-air duration of a MAC frame can lead to increased interference potential, susceptibility to channel conditions changing during the duration of a MAC frame transmission, and other effects that may reduce reliable transfer in some environments typical of LECIM applications. The long packet duration also brings a large cost for retransmission, both in terms of energy consumed and interference footprint.

MPDU fragmentation can improve the probability of successful transmission and reduce the cost of retransmission. With fragmentation, each fragment is packaged into a PPDU for transmission, and this smaller PPDU has a reduced interference footprint. Also, retransmissions can be performed on a per fragment basis without needing to retransmit the entire original packet.

The Simplified Superframe Specification IE is intended to reduce the amount of communications between the PAN coordinator and end devices. This allows an enhanced beacon with the Simplified Superframe Specification IE to be transmitted in a single PPDU when the LECIM DSSS PHY is in use.

MPDU fragmentation operates on the MHR and MSDU portions of the MPDU transparent to other MAC MPDU processing. MPDU fragmentation is specified so that it may be used with any of the PHYs defined in this standard. Optimum use of fragmentation depends on many variables, including channel performance, the interference environment, and characteristics of the PHY selected (e.g., data rate and maximum PSDU size supported). An overview of the fragmentation process is shown in Figure Q.1.

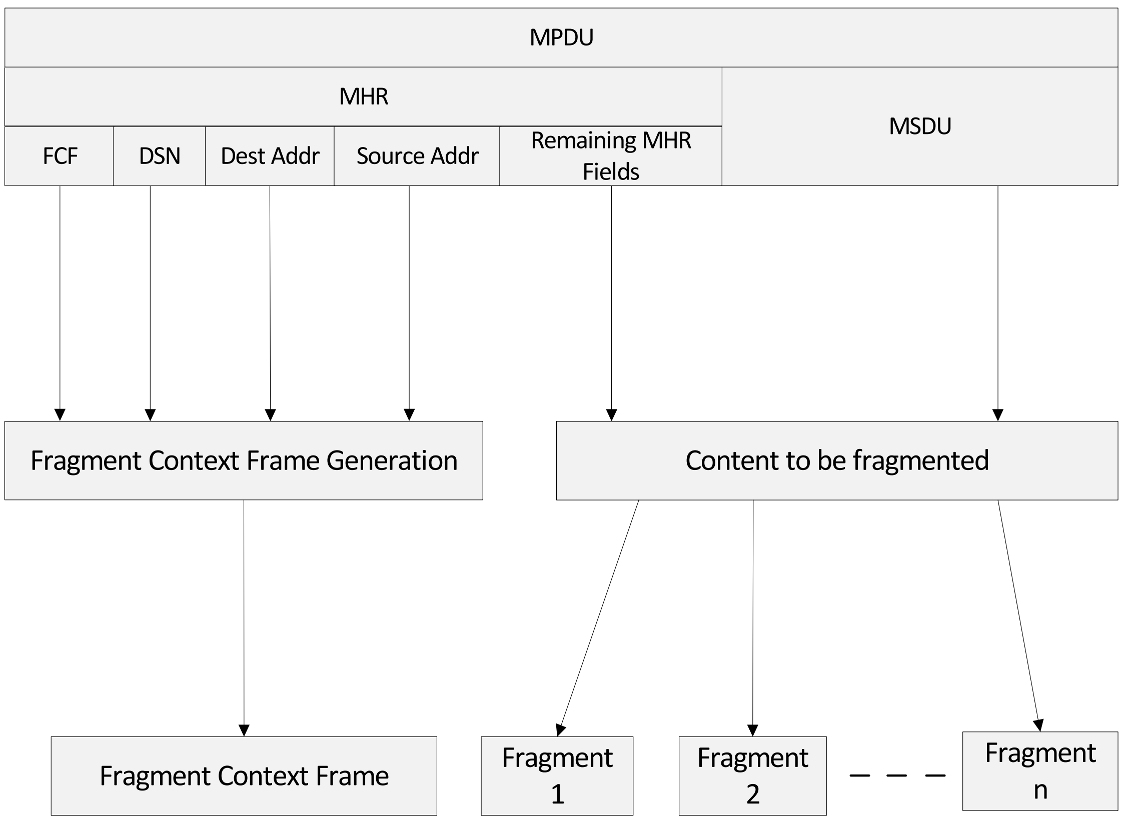


Figure Q.1—Fragmentation process overview

When the LECIM DSSS PHY is being used, the PSDU size may be from 16 to 32 octets. A typical MPDU may be substantially larger than the available PSDU size. Fragmentation enables all the MAC frame formats defined by this standard to be carried in the constrained PSDU size. Fragmentation operates on the complete MPDU and adapts it to the characteristics of the specific PHY and PHY operating mode. The fragment size is determined by the value of *phyLECIMDSSSPSDUSize*. The following example illustrates how MPDU fragmentation may be applied to the LECIM DSSS PHY.

The LECIM DSSS PHY allows for a unique code to be assigned to a link between the end-point and the PAN coordinator. For this example, consider a unique code that is assigned for the down-link between the

PAN coordinator and the device. Down-link addressing information is implied, and the probability of a TID collision is nil. A context setup frame in this example, shown in Figure Q.2, would be a multipurpose frame with no DSN, no addressing, no auxiliary security header, and exactly one MPDU Fragment Sequence Context Description IE.

Octets: 2	6	4
FCF	MPDU Fragment Sequence Context Description IE	FCS
MHR	MAC Payload	MFR

Figure Q.2—Context setup frame when using LECIM DSSS PHY

The fragment size is

$$phyLECIMDSSSPSDUSize - 2 - V$$

where V is 2 when *macFragmentCVSType* is set to 16, and V is 4 when *macFragmentCVSType* is set to 32.

Q.2.4 Frame priority

Frame priority allows LECIM networks to exhibit low latencies for truly critical event messages versus those latencies for link maintenance or other lower priority messages.

Frame priority is established by two means: PCA allocations and the PCA backoff algorithm, described in 5.1.1.4.5 for CSMA-CA and 5.1.1.4a for CCA Mode 4 (ALOHA). Both algorithms are used during contention access, but the PCA allocations can only be used when operating in beacon-enabled mode. The PCA is only usable for critical event messages, but the critical event messages do have to compete with each other for access to the channel.

The PCA backoff algorithm is used whenever contention access is applied. It operates slightly differently based on whether CCA Mode 4 (ALOHA) is used or not. The conditions for CCA Mode 4 (ALOHA) are described in 5.1.1.4a. When CCA Mode 4 (ALOHA) is not used, the transmitting device remains in persistent mode, as described in 5.1.1.4.5.

Q.2.5 TRLE

For extending the range of a link in a star network composed of beacon-enabled devices or DSME-enabled devices, the TRLE PAN relays residing between the PAN coordinator and devices support transparent link connectivity without additional networking overhead to an end device.

The TRLE PAN relay operates with the frame filtering in relaying mode and relays MAC frames either in the direction of the PAN coordinator or in the direction of a device. The TRLE PAN relay provides a one-hop relaying link extension for the beacon-enabled PAN. The TRLE-enabled PAN coordinator and the TRLE PAN relays provide multi-hop relaying link extension for the DSME-enabled PAN.

Q.2.6 PIB attributes

LECIM mechanisms and protocols in this standard require the following additional PIB attributes.

MAC PIB attributes

— *macLECIMAlohaUnitBackoffPeriod*
— *macLECIMAlohaBE*
— *macMPDUFragPadValue*
— *macFragmentFVSType*
— *macFVSoffset*
— *macFVSRIV*
— *macRelayingMode*
— *macTRLEenabled*

PCA-specific PIB attributes

— *macPriorityChannelAccess*
— *macPCAAllocationSuperRate*
— *macPCAAllocationRate*
— *macCritMsgDelayTol*

DSME-specific MAC PIB attributes

— *macAllocationOrder*
— *macBIIndex*
— *macExtendedDSMEcapable*
— *macExtendedDSMEenabled*

LE-specific MAC PIB attributes

— *macIRITOffsetInterval*
— *macIRITListenDuration*
— *macIRITEnabled*

The TRLE-specific MAC PIB attributes are given in Table S.6 of S.5.4.

The PHY PIB attributes are given in Table 71 of 9.3.

Q.2.7 IEs

LECIM mechanisms and protocols in this standard require the following IEs:

— Extended DSME PAN Descriptor IE (5.2.4.9a)
— PHY Parameter Change IE (5.2.4.23)
— MPDU Fragment Sequence Context Description IE (5.2.4.25)
— LECIM DSSS Capabilities IE (5.2.4.28)
— DSSS Operating Mode Description IE (5.2.4.29.1)
— FSK Operating Mode Description IE (5.2.4.29.2)
— TRLE Descriptor IE (S.5.1.1)

Q.2.8 PHY parameter changes for fragment sequence exchange

Given the potentially long duration of the MPDU transaction in time, there is a possibility that channel conditions may change significantly. The higher layer may decide that the channel is becoming unusable and desire to change to another channel for subsequent transactions. The PHY Parameter Change IE is described in 5.2.4.23.

The PHY Parameter Change IE may be included in a directed frame, which facilitates changing PHY operating parameters between the specific sender and receiver.

If a device determines that a switch in band, channel, or other PHY operating parameter is necessary during a fragmentation sequence transaction, the device should terminate the transaction context as described in 5.4.1 or 5.4.2. Following the termination, a MAC frame with the PHY Parameter Change IE is sent by the device initiating the change. The originator may switch to the new PHY parameters upon reception of an acknowledgment.

The higher layer network management entity controls which channel and/or PHY configurations are used to communicate with which neighboring devices; the process by which this is done is outside the scope of this standard.

Annex R

(informative)

Example results from 384 bit LECIM DSSS PHY blocked interleaver

R.1 Introduction

The sequence of *N* is shown in Table R.1. For more information, see 19.1.2.4.2.

Table R.1—Sequence of *N* for 384-bit fragment size (pruned)

	Bit: 0	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Octet: 0	000	256	128	064	320	192	032	288
1	160	096	352	224	016	272	144	080
2	336	208	048	304	176	112	368	240
3	008	264	136	072	328	200	040	296
4	168	104	360	232	024	280	152	088
5	344	216	056	312	184	120	376	248
6	004	260	132	068	324	196	036	292
7	164	100	356	228	020	276	148	084
8	340	212	052	308	180	116	372	244
9	012	268	140	076	332	204	044	300
10	172	108	364	236	028	284	156	092
11	348	220	060	316	188	124	380	252
12	002	258	130	066	322	194	034	290
13	162	098	354	226	018	274	146	082
14	338	210	050	306	178	114	370	242
15	010	266	138	074	330	202	042	298
16	170	106	362	234	026	282	154	090
17	346	218	058	314	186	122	378	250
18	006	262	134	070	326	198	038	294

Table R.1—Sequence of *N* for 384-bit fragment size (pruned) *(continued)*

	Bit: 0	1	2	3	4	5	6	7
19	166	102	358	230	022	278	150	086
20	342	214	054	310	182	118	374	246
21	014	270	142	078	334	206	046	302
22	174	110	366	238	030	286	158	094
23	350	222	062	318	190	126	382	254
24	001	257	129	065	321	193	033	289
25	161	097	353	225	017	273	145	081
26	337	209	049	305	177	113	369	241
27	009	265	137	073	329	201	041	297
28	169	105	361	233	025	281	153	089
29	345	217	057	313	185	121	377	249
30	005	261	133	069	325	197	037	293
31	165	101	357	229	021	277	149	085
32	341	213	053	309	181	117	373	245
33	013	269	141	077	333	205	045	301
34	173	109	365	237	029	285	157	093
35	349	221	061	317	189	125	381	253
36	003	259	131	067	323	195	035	291
37	163	099	355	227	019	275	147	083
38	339	211	051	307	179	115	371	243
39	011	267	139	075	331	203	043	299
40	171	107	363	235	027	283	155	091
41	347	219	059	315	187	123	379	251
42	007	263	135	071	327	199	039	295
43	167	103	359	231	023	279	151	087
44	343	215	055	311	183	119	375	247
45	015	271	143	079	335	207	047	303

Table R.1—Sequence of *N* for 384-bit fragment size (pruned) *(continued)*

	Bit: 0	1	2	3	4	5	6	7
46	175	111	367	239	031	287	159	095
47	351	223	063	319	191	127	383	255

Annex S

(normative)

Time-slot relaying based link extension (TRLE)

S.1 General

In a star topology, the range of the network is limited by the transmission and reception range of the devices forming a link. There are occasions when a further range extension of the network may be required. An example would be when supporting a very sparse dispersion of devices beyond the radio range of a PAN coordinator to an end device. Another example may arise when maintaining connection with an end device where the RF environment degrades as a result of geographic change after the initial deployment.

A PAN relay is a coordinator that relays IEEE Std 802.15.4 MAC frames either in the direction of the PAN coordinator or in the direction of a device. This annex provides specific MAC capabilities for extending the range of a link in a star network composed of the IEEE 802.15.4 beacon-enabled devices or the IEEE 802.15.4 DSME-enabled devices. The TRLE PAN relays residing between the PAN coordinator and devices support transparent link connectivity without additional networking overheads to an end device.

Some of the capabilities provided by this annex are as follows:

- Frame filtering in relaying mode
- Frame relaying on a link between the IEEE 802.15.4 beacon-enabled PAN coordinator and devices
- Management of multi-hop relaying path between the TRLE-enabled PAN coordinator and devices
- Frame relaying on a TRLE multi-hop path

S.2 Link extension for a beacon-enabled PAN

The TRLE PAN relay extends the link of a beacon-enabled PAN by relaying frames at the MAC sublayer in direction to a device (i.e., outward relaying) or in direction to the PAN coordinator (i.e., inward relaying).

The TRLE PAN relay provides a one-hop relaying link extension for the IEEE 802.15.4 beacon-enabled PAN. The TRLE-enabled PAN coordinator and the TRLE PAN relays provide multi-hop relaying link extension for the IEEE 802.15.4 DSME-enabled PAN.

The TRLE PAN relay may be used in several beacon-enabled PAN configurations, as shown in Figure S.1: (a) beacon-enabled PAN coordinator - TRLE PAN relay - non-TRLE device, (b) TRLE-enabled PAN coordinator - multiple TRLE PAN relays - DSME-enabled device or TRLE-enabled device.

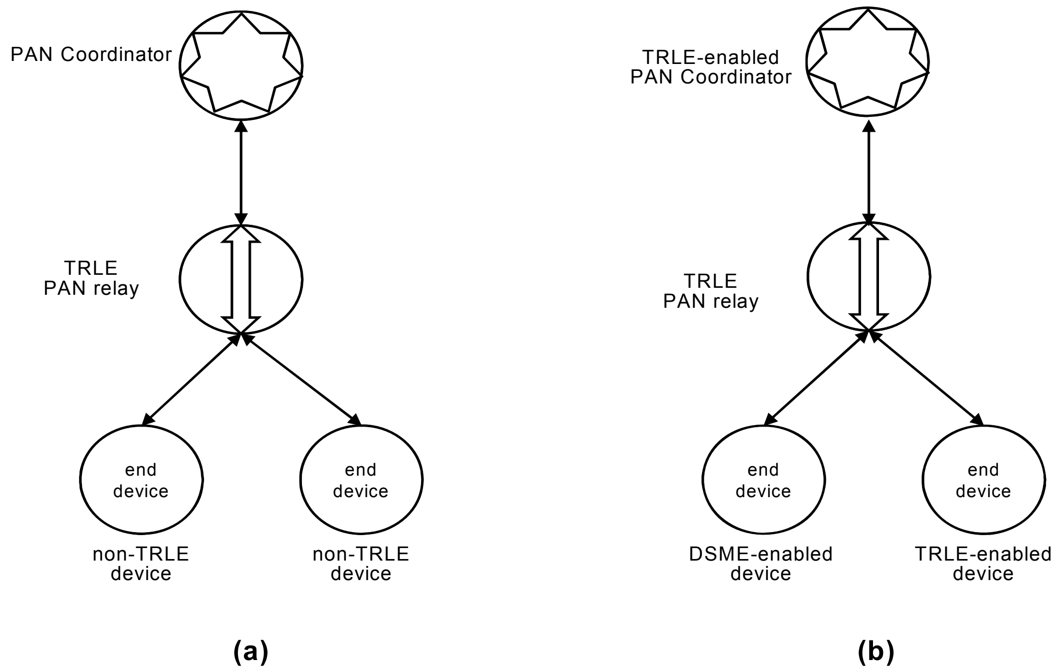


Figure S.1—Usage of the TRLE PAN relay

S.3 Link extension for the non-TRLE PAN

S.3.1 TRLE PAN relay association and disassociation

An FFD shall perform as a TRLE PAN relay if the PIB attributes *macTRLEenabled* and *macRelayingMode* are set to TRUE. A TRLE PAN relay shall associate as a coordinator with the beacon-enabled PAN, as described in 5.1.3.1.

After completing association, the next higher layer may initiate relaying frames at the MAC sublayer by issuing the MLME-TRLE-MANAGEMENT.request primitive with the ManagementType parameter set to RELAY_ON, as described in S.5.3.1, that the MLME shall configure *macSyncRelayingOffset* to be set equal to the SyncRelayingOffset parameter of the MLME-TRLE-MANAGEMENT.request primitive.

The MAC sublayer of the TRLE PAN relay shall begin relaying frames, as described in S.3.3. The next higher layer shall be notified of the result of initiating the TRLE PAN relay through the MLME-TRLE-MANAGEMENT.confirm primitive with ManagementType parameter set to RELAY_ON and status parameter, as described in S.5.3.4.

If the TRLE PAN relay wants to leave the PAN, the next higher layer may halt the relaying by issuing the MLME-TRLE-MANAGEMENT.request primitive with the ManagementType parameter set to RELAY_OFF, as described in S.5.3.1. The next higher layer shall be notified of the result of halting the TRLE PAN relay through the MLME-TRLE-MANAGEMENT.confirm primitive with ManagementType parameter set to RELAY_OFF and status parameter, as described in S.5.3.4.

After halting the relaying, the TRLE PAN relay shall disassociate with the beacon-enabled PAN, as described in 5.1.3.2.

S.3.2 Frame filtering in relaying mode

In relaying mode (i.e., *macRelayingMode* set to TRUE), the MAC sublayer shall maintain the first level of filtering and the second level of filtering described in 5.1.6.2 and accept only frames that satisfy all of the third level filtering requirements except matching of a destination address.

If the frame is valid, the MAC sublayer either passes the frame to the next higher layer or relays the frame onward according to the destination address. The frame having its destination addresses as the broadcast address shall be passed to the next higher layer and be also relayed onward.

S.3.3 One-hop relaying

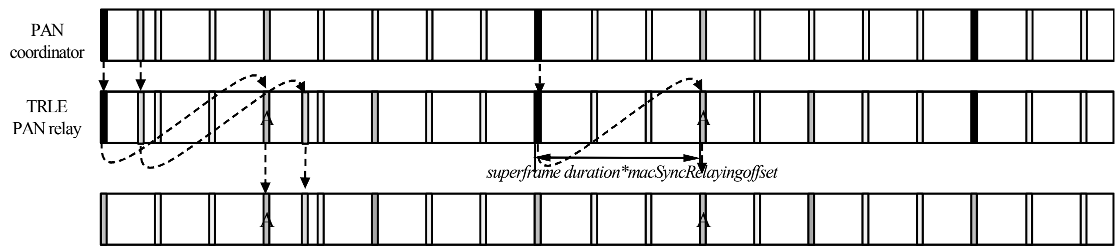
The TRLE PAN relay for the IEEE 802.15.4 beacon-enabled PAN or the IEEE 802.15.4 DSME-enabled PAN provides one-hop relaying to extend the range of the link.

If a short destination address included in the frame matches *macShortAddress*, or if an extended destination address included in the frame matches *macExtendedAddress*, the frame shall be handled as described in 5.1.6.2.

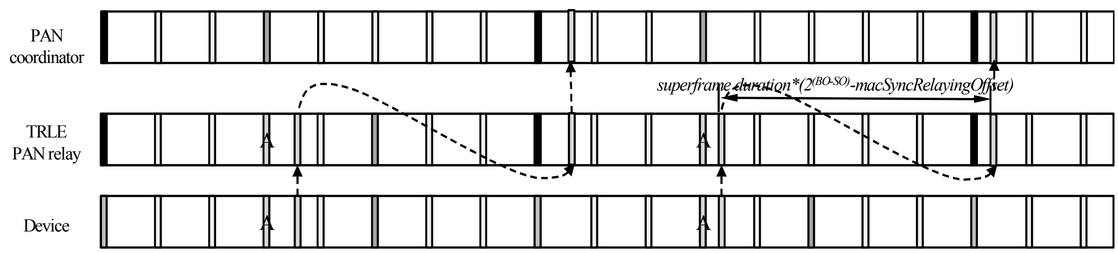
A frame with a destination address equal to the broadcast address shall be handled as described in 5.1.6.2 and shall also be relayed by the MAC sublayer.

If a short destination address included in the frame does not match *macShortAddress*, or if an extended destination address included in the frame does not match *macExtendedAddress*, the frame shall be relayed by the MAC sublayer.

Frames received from the PAN coordinator shall be relayed after delaying $superframe\ duration \times macSynchRelayingOffset$, and frames received from the device shall be relayed after delaying $superframe\ duration \times [2^{(BO-SO)} - macSynchRelayingOffset]$, as shown in Figure S.2. The delay for relaying is determined by the TRLE PAN relay, when associating with the beacon-enabled PAN. The algorithm for choosing *macSynchRelayingOffset* is outside the scope of this standard.



(a) outward one-hop relaying



(b) inward one-hop relaying

Figure S.2—Relaying frames for the beacon-enabled PAN coordinator and a device

S.4 Link extension for the TRLE-enabled PAN

S.4.1 TRLE-enabled PAN

The PAN coordinator of a DSME-enabled PAN shall perform as a TRLE-enabled PAN coordinator, if the PIB attribute *macTRLEenabled* is set to TRUE. The TRLE-enabled PAN coordinator may provide a multi-hop relaying path with the TRLE PAN relays.

Beacon frames from the TRLE-enabled PAN coordinator received by the PAN relays within the transmission range of the PAN coordinator from tier 1 of the TRLE-enabled PAN. The PAN relays that are within a transmission range of the tier 1 PAN relays, but not within PAN coordinator range, form tier 2 of the TRLE-enabled PAN, and so on, as illustrated in Figure S.3. For any given PAN relay, a neighboring PAN relay closer to the PAN coordinator is called an inner PAN relay and a PAN relay closer to the end device is called an outer PAN relay. The relaying of a TRLE-enabled PAN is limited to seven tiers.

The TRLE-enabled PAN coordinator and the PAN relay use a cyclic-superframe structure. The cyclic-superframe structure is based on the DSME multi-superframe structure, as illustrated in Figure S.4.

The CAP is divided into time slots for transmitting a frame to the PAN coordinator (i.e., the prioritized device time slot) and time slots for transmitting a frame to end devices (i.e., the coordinator time slot). The prioritized device time slot starts after the beacon and continues for a preset number of time slots, *macNumPrioritizedDeviceSlot*. The coordinator time slot starts after the prioritized device time slot and continues for a preset number of time slots, *macNumCoordSlot*.

The time slot in CFP is bidirectional (i.e., the bidirectional device time slot). The bidirectional device time slots for a TRLE PAN relay or TRLE-enabled device may be pre-assigned or allocated before use.

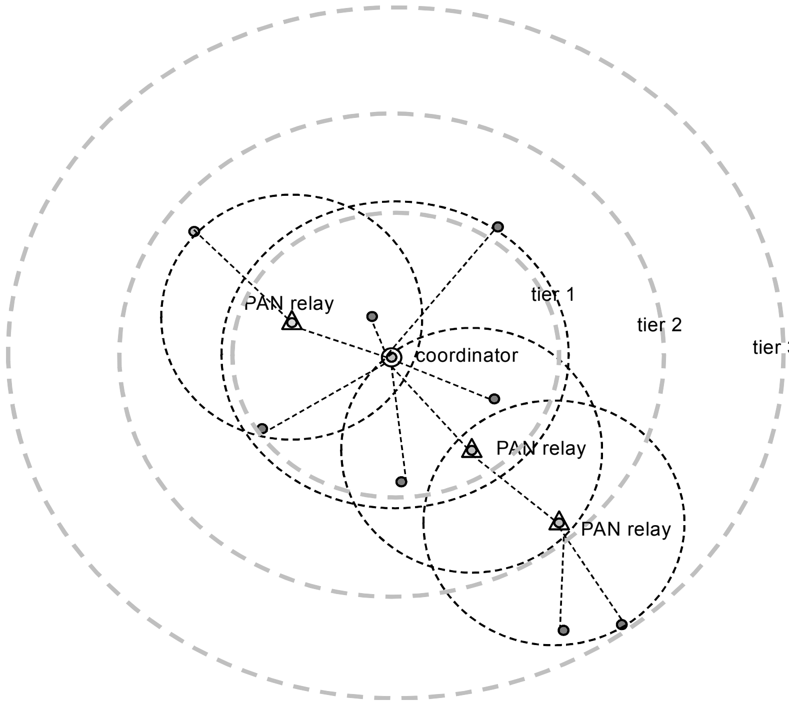


Figure S.3—Hierarchy of relaying in the TRLE-enabled PAN

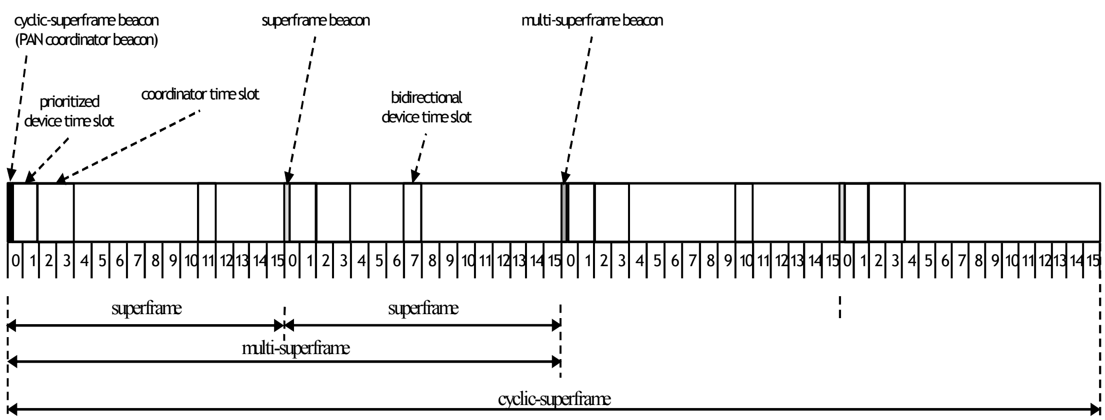


Figure S.4—Time slots in a TRLE cyclic-superframe

S.4.2 Starting a TRLE-enabled PAN

A PAN coordinator with PIB attributes *macDSMEenabled* and *macTRLEenabled* set to TRUE shall start a DSME-enabled PAN by following the procedure described in 5.1.2.3.1.

The PAN coordinator shall be instructed to begin operating as the TRLE-enabled PAN coordinator through the use of the MLME-TRLE-MANAGEMENT.request primitive, as described in S.5.3.1, with the ManagementType parameter set to START.

On receipt of this primitive, the MLME configures the following MAC PIB attributes:

- *macNumPrioritizedDevice* shall be set equal to the NumPrioritizedDevice parameter of the MLME-TRLE-MANAGEMENT.request primitive.
- *macNumCoordSlot* shall be set equal to the NumCoordSlot parameter of the MLME-TRLE-MANAGEMENT.request primitive.

After completing this, the MAC sublayer shall issue the MLME-TRLE-MANAGEMENT.confirm primitive with the ManagementType parameter set to START and a status of SUCCESS, as described in S.5.3.4, and begin operating as the TRLE-enabled PAN coordinator.

The TRLE-enabled PAN is formed when the TRLE-enabled PAN coordinator advertises the presence of the TRLE-enabled PAN by sending an enhanced beacon, which contains the DSME PAN descriptor IE and the TRLE descriptor IE, as defined in S.5.1.1.

S.4.3 TRLE relaying path formation

An FFD having PIB attributes *macDSMEenabled*, *macTRLEenabled*, and *macRelayingMode* set to TRUE shall perform as a TRLE PAN relay. An RFD having PIB attributes *macDSMEenabled* and *macTRLEenabled* set to TRUE shall perform as a TRLE-enabled device.

The next higher layer of a TRLE PAN relay or TRLE-enabled device shall perform a MAC sublayer reset, by issuing the MLME-RESET.request primitive with the SetDefaultPIB parameter set to TRUE, and then complete either an active or a passive channel scan, as defined in 5.1.2.1.2. The results of the channel scan should be used to choose a suitable PAN and to select an inner coordinator, either the TRLE-enabled PAN coordinator or an inner TRLE PAN relay, through which it will attempt to associate.

Following the selection of a TRLE-enabled PAN, a TRLE PAN relay or a TRLE-enabled device shall be instructed to associate with a DSME-enabled PAN, as described in 5.1.3.1.

After completing association, the next higher layer may instruct through the MLME-TRLE-MANAGEMENT.request primitive with the ManagementType parameter set to JOIN and the TxGrade parameter set to GRADE_0 for the TRLE PAN relay or set to GRADE_2 for the TRLE-enabled device, as described in S.5.3.1, that the MLME configures the following MAC PIB attributes:

- *macRelayingTier* shall be set equal to the SrcRelayingTier parameter of the MLME-TRLE-MANAGEMENT.request primitive.
- *macInnerRelayingOffset* shall be set equal to the InnerRelayingOffset parameter of the MLME-TRLE-MANAGEMENT.request primitive.
- *macNumBidirectionalDeviceSlot* shall be set equal to the NumBidirectionalDeviceSlot parameter of the MLME-TRLE-MANAGEMENT.request primitive.

The MAC sublayer shall initiate the joining procedure by sending a TRLE-Management request command with the Management Type field set to Join, as described in S.5.2.1. The TRLE Descriptor IE shall be included in the Header IE field of the TRLE-Management request command. The TxGrade parameter of the request primitive is set to the Grade of Link Access field of the TRLE Descriptor IE. The time slot in which the TRLE-Management request command will be transmitted shall be selected by the InnerRelayingOffset parameter.

When relaying a TRLE-Management request command with the Management Type field set to Join, the PAN relay collects a source address of the MHR fields and the PAN Relay Address field of the TRLE Descriptor IE of the frame relayed, and updates the *macPANRelayList*.

The TRLE-enabled PAN coordinator indicates the reception of a TRLE-Management request command through the MLME-TRLE-MANAGEMENT.indication primitive with the ManagementType parameter set to JOIN, as described in S.5.3.2. The Grade of Link Access field of the TRLE Descriptor IE is set to the TxGrade parameter of the indication primitive.

The next higher layer of the TRLE-enabled PAN coordinator shall assign time slots in a cyclic-superframe for the bidirectional device slot and determine the relaying delay at the TRLE PAN relay requesting the TRLE path formation with information provided by the BeaconBitmap parameter and RelayingPathList parameter of indication primitive. The algorithm for choosing the relaying delay is outside the scope of this standard. If a time slot is not available, the next higher layer may issue the MLME-TRLE-MANAGEMENT.response primitive with ManagementType parameter set to JOIN and a status of SLOT_FULL. If it fails to determine the relaying delay, the next higher layer may issue the MLME-TRLE-MANAGEMENT.response primitive with ManagementType parameter set to JOIN and a status of RELAY_FULL. Otherwise, the next higher layer of the TRLE-enabled PAN coordinator may initiate a response using an MLME-TRLE-MANAGEMENT.response primitive with the ManagementType parameter set to JOIN and a status of SUCCESS, as described in S.5.3.3.

When the MLME of the TRLE PAN coordinator receives the MLME-TRLE-MANAGEMENT.response primitive, it generates a TRLE-Management response command with the Management Type field set to Join, as described in S.5.2.2, and attempts to send a command to the device requesting TRLE path formation. The time slot in which the TRLE-Management response command frame will be transmitted shall be selected according the TxGrade parameter of the response primitive, as described in S.4.6. The identifier of the time slot is set to the Slot ID field and the Superframe ID field of the TRLE Descriptor IE. The TxGrade parameter of the response primitive is set to the Grade of Link Access field of the TRLE Descriptor IE. The Timestamp field of the TRLE-Management response command is set to the time of the time slot specified by the Slot ID field and the Superframe ID field of the TRLE Descriptor IE. The TRLE Descriptor IE shall be included in the Header IE field of the TRLE-Management response command.

On reception of the TRLE-Management response command, the TRLE PAN relay or TRLE-enabled device informs the next higher layer of the association response by using an MLME-TRLE-MANAGEMENT.confirm primitive with the ManagementType parameter set to JOIN, as described in S.5.3.4.

After joining a TRLE path, the next higher layer of the TRLE PAN relay may instruct through the MLME-TRLE-MANAGEMENT.request primitive with the ManagementType parameter set to RELAY_ON, as described in S.5.3.1, that the MLME configures the following MAC PIB attributes:

— *macNumPrioritizedDevice* shall be set equal to the NumPrioritizedDevice parameter of the MLME-TRLE-MANAGEMENT.request primitive.
— *macNumCoordSlot* shall be set equal to the NumCoordSlot parameter of the MLME-TRLE-MANAGEMENT.request primitive.
— *macSyncRelayingOffset* shall be set equal to the SyncRelayingOffset parameter of the MLME-TRLE-MANAGEMENT.request primitive.

The MAC sublayer of the TRLE PAN relay shall begin relaying frames, as described in S.4.4. The next higher layer shall be notified of the result of initiating the PAN relay through the MLME-TRLE-MANAGEMENT.confirm primitive with the ManagementType parameter set to RELAY_ON, as described in S.5.3.4.

In order for the TRLE PAN relay or TRLE-enabled device to leave the TRLE-enabled PAN, the next higher layer should halt the relaying by issuing the MLME-TRLE-MANAGEMENT.request primitive with the ManagementType parameter set to RELAY_OFF. The next higher layer shall be notified of the result of halting the relaying through the MLME-TRLE-MANAGEMENT.confirm primitive with the ManagementType parameter set to RELAY_OFF, as described in S.5.3.4.

After halting the relaying, the next higher layer may request through the MLME-TRLE-MANAGEMENT.request primitive with the ManagementType parameter set to LEAVE and TxGrade parameter set to GRADE_0 for the TRLE PAN relay or set to GRADE_2 for the TRLE-enabled device, as described in S.5.3.1.

The MAC sublayer of the TRLE PAN relay shall initiate the leaving procedure by sending a TRLE-Management request command with the Management Type field set to Leave, as described in S.5.2.1, through the inner coordinator to the TRLE-enabled PAN coordinator.

The TRLE-enabled PAN coordinator indicates the reception of a TRLE-Management request command through the MLME-TRLE-MANAGEMENT.indication primitive with the ManagementType parameter set to LEAVE, as described in S.5.3.2. The next higher layer of the TRLE PAN coordinator may confirm that the device requesting disassociation is on a relaying path and determine whether it is possible to leave the relaying path.

If it is admitted, the next higher layer of the TRLE-enabled PAN coordinator may initiate a response using an MLME-TRLE-MANAGEMENT.response primitive with the ManagementType parameter set to LEAVE and a status of SUCCESS, as described in S.5.3.3. Otherwise, the status parameter of the response primitive is set to NOT_FOUND or NOT_CONFIRMED.

When the MLME of the TRLE PAN coordinator receives the MLME-TRLE-MANAGEMENT.response primitive, it generates a TRLE-Management response command with the Management Type field set to Leave, as described in S.5.2.2, and attempts to send the command to the requesting device.

On the reception of the TRLE-Management response command, the TRLE PAN relay or TRLE-enabled device informs the next higher layer using an MLME-TRLE-MANAGEMENT.confirm primitive with ManagementType parameter set to LEAVE, as described in S.5.3.4. The status parameter in the MLME-TRLE-MANAGEMENT.confirm primitive is set to the Management Status field of the Management response command.

After leaving a TRLE path, the next higher layer may disassociate from the DSME-enabled PAN, as described in 5.1.3.2.

S.4.4 Multi-hop relaying

The TRLE-enabled PAN coordinator and TRLE PAN relays may provide multi-hop relaying to extend the range of the link.

On receipt of a frame, the MAC sublayer of a TRLE PAN relay shall perform frame filtering, as described in S.3.2.

If a short destination address included in the filtered frame matches *macShortAddress*, or if an extended destination address included in the filtered frame matches *macExtendedAddress*, the frame shall be handled as described in 5.1.6.2.

A frame having a destination address as the broadcast address shall be handled as described in 5.1.6.2 and shall also be relayed by the MAC sublayer.

If a short destination address included in the filtered frame does not match *macShortAddress*, or if an extended destination address included in the filtered frame does not match *macExtendedAddress*, the frame shall be relayed at the MAC sublayer.

If the Relaying Direction field of the TRLE Descriptor IE is set to one and the Relaying Tier Identifier field is equal to $macRelayingTier - 1$, the frame shall be relayed outward. If the Relaying Direction field of the TRLE Descriptor IE is set to zero and the Relaying Tier Identifier field is equal to $macRelayingTier + 1$, the frame shall be relayed inward. Otherwise, the TRLE PAN relay shall discard the frame.

If the PAN Relay Address field of the TRLE Descriptor IE included in the relayed outward frame, with the exception of a beacon frame, does not match *macShortAddress*, the TRLE PAN relay shall discard the frame. If the PAN Relay Address field of the TRLE Descriptor IE included in the relayed inward frame, with the exception of a TRLE-Management request command with the Management Type field set to Join, does not match one of the outer adjacent PAN relays in the *macPANRelayList*, the TRLE PAN relay shall discard the frame.

If the frame is the TRLE-Management request command with the Management Type field set to Join or the TRLE-Management response command with the Management Type field set to Path, the PAN relay List Count field of the Relaying Path List field is increased by one and the TRLE Descriptor IE is copied to the end of the PAN relay List field of the Relaying Path List field of the command frame.

Before relaying the frame, the TRLE Descriptor IE shall be updated. The Relaying Tier Identifier field is changed to the PIB attribute *macRelayingTier*. The TRLE PAN Relay Address field of a beacon frame or the frame relayed inward is changed to the PIB attribute *macShortAddress*. The TRLE PAN Relay Address field of the relayed outward frame, with the exception of a beacon, is changed to one of the outer adjacent PAN relays in the *macPANRelayList*, indexed by the destination address of the MHR fields. The Slot ID field and Superframe ID field are set to the time slot assigned for relaying the frame, as described in S.4.6.

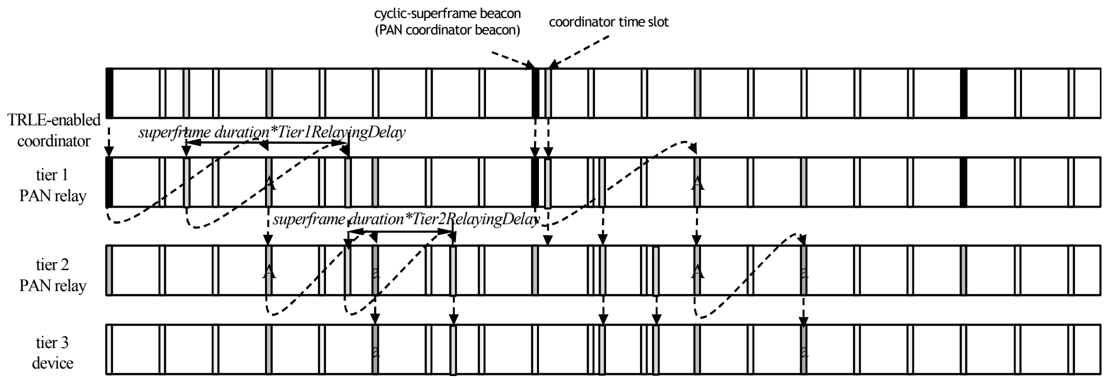
If the Grade of Link Access field of the TRLE Descriptor IE is set to 0b00 or 0b01, the Frame Type field indicates a data or MAC command frame relayed inward and the AR field is set to request an acknowledgment, the MAC sublayer shall send an acknowledgment frame having a destination address set to the TRLE PAN Relay Address field of the TRLE Descriptor IE. Prior to the transmission of the acknowledgment frame, the sequence number included in the received data or MAC command frame shall be copied into the Sequence Number field of the acknowledgment frame, and the TRLE Descriptor IE shall be included in the Header IE of the acknowledgment frame.

The frame is relayed either outward or inward, as shown in Figure S.5. The beacon generated by the TRLE PAN coordinator shall be relayed outward after delaying $superframe\ duration \times \mathrm{RelayingDelay}$. The RelayingDelay is calculated as $macSyncRelayingOffset - macInnerRelayingOffset$, if *macSyncRelayingOffset* is larger than *macInnerRelayingOffset*. Otherwise, the RelayingDelay is calculated as $2^{(BO - SO)} - (macInnerRelayingOffset - macSyncRelayingOffset)$.

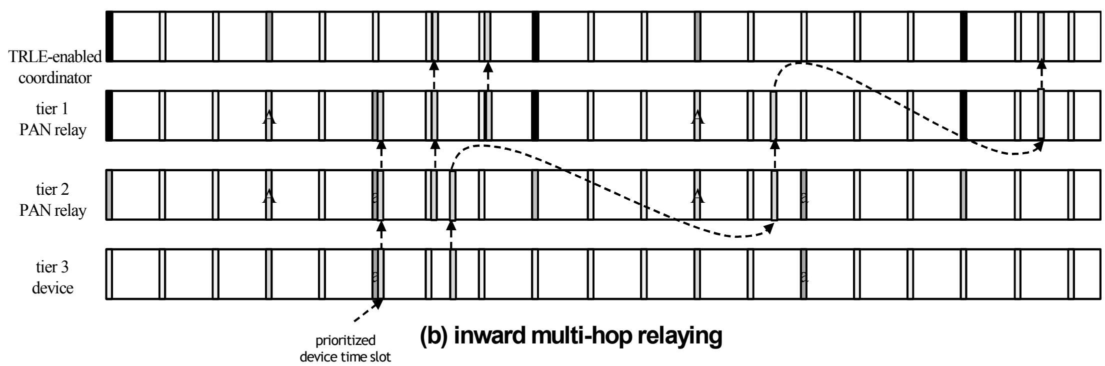
The frame received in a prioritized device time slot shall be relayed inward within the prioritized device time slot. If transmission cannot be completed by the end of the prioritized device time slot, the frame shall be relayed in the prioritized device time slot of the next superframe.

The frame received in a coordinator time slot shall be relayed outward within the coordinator time slot. If transmission cannot be completed by the end of the coordinator time slot, the frame shall be relayed in the coordinator time slot of the next superframe.

The frame received in a bidirectional device time slot from the inner PAN relay shall be relayed outward after delaying $superframe\ duration \times \mathrm{RelayingDelay}$. The frame received from the outer PAN relay shall be relayed after delaying $superframe\ duration \times [2^{(BO - SO)} - \mathrm{RelayingDelay}]$.



(a) outward multi-hop relaying



(b) inward multi-hop relaying

Figure S.5—Synchronous multi-hop frame relaying

S.4.5 TRLE path maintenance

After starting a TRLE-enabled PAN, the PAN coordinator may need to check the status of a device, collect information on the configuration of PAN relays on the TRLE relaying paths, and maintain time-synchronization.

To search for activated devices in a TRLE-enabled PAN, the next higher layer may issue the MLME-TRLE-MANAGEMENT.request primitive with the ManagementType parameter set to HELLO and the DstAddr parameter, as described in S.5.3.1. The TRLE-enabled PAN coordinator only shall be allowed to set the DstAddr parameter of the request primitive to the broadcast address.

The MAC sublayer shall send the TRLE-Management request command with the Management Type field set to Hello.

The MLME shall notify the reception of a TRLE-Management request command through the MLME-TRLE-MANAGEMENT.indication primitive with the ManagementType parameter set to HELLO. If the destination address of the TRLE-Management request command is set to the broadcast address, the MAC sublayer shall relay the TRLE-Management request command to the outer PAN relays in the *macPANRelayList*.

The next higher layer may set the device configuration, as defined in S.5.2.2.7, through the MLME-TRLE-MANAGEMENT.response primitive, defined in S.5.3.3, with the ManagementType parameter set to HELLO.

When the MLME receives the MLME-TRLE-MANAGEMENT.response primitive with the ManagementType parameter set to HELLO, it generates a TRLE-Management response command with the Management Type field set to Hello, as described in S.5.2.2, and attempts to send the response command to the requesting device.

The next higher layer shall be notified of a reception of a TRLE-Management response command with the Management Type field set to Hello, through the MLME-TRLE-MANAGEMENT.confirm primitive with ManagementType parameter set to HELLO.

To get information on the relaying path configuration to a device, the next higher layer may issue the MLME-TRLE-MANAGEMENT.request primitive with the ManagementType parameter set to PATH.

The MAC sublayer shall send the TRLE-Management request command with the Management Type field set to Path, as described in S.5.2.1. The request command shall be relayed to the destination device.

The MLME shall notify the next higher layer of the reception of a TRLE-Management request command with the Management Type field set to Path by issuing the MLME-TRLE-MANAGEMENT.indication primitive with the ManagementType parameter set to PATH.

The next higher layer may report the device configuration, as defined in S.5.2.2.7, through the MLME-TRLE-MANAGEMENT.response primitive with the ManagementType parameter set to PATH.

When the MLME receives the MLME-TRLE-MANAGEMENT.response primitive with the ManagementType parameter set to PATH, it generates a TRLE-Management response command with the Management Type field set to Path, as described in S.5.2.2, and attempts to send command to the device requesting the path configuration. The relaying path configuration is added to the Relay Path List field of the TRLE-Management response command at the MAC sublayer of the PAN relays on the relaying path to the requesting device, as described in S.4.4.

The next higher layer shall be notified a reception of a TRLE-Management response command with the Management Type field set to Path, through the MLME-TRLE-MANAGEMENT.confirm primitive with the ManagementType parameter set to PATH, as described in S.5.3.4.

The PAN relays and end devices in a TRLE-enabled PAN shall be synchronized with the time of the TRLE-enabled PAN coordinator after joining the TRLE-enabled PAN.

The TRLE-enabled PAN coordinator shall advertise the time, obtained from the local clock of the TRLE-enabled PAN, outward to the PAN relays and end devices via the Beacon Timestamp field of the DSME PAN descriptor IE in a beacon frame. The time, obtained from the local clock of a TRLE PAN relay, may be distributed via the Timestamp field in the TRLE-Management request command and the TRLE-Management response command. The Timestamp field shall specify the start time of a time slot where the frame is to be transmitted.

The PAN relays and end devices compensate for the clock drift based on the statistical variance of the difference in the real start time of a given slot and the expected start time.

The PAN relay maintains the status of the neighbored PAN relays by watching the beacon frame of the inner PAN relay and of the outer PAN relay.

If the PAN relay misses the beacon frame of the inner PAN relay for $macBeaconMissingLimit \times BI$, the PAN relay selects one of the adjacent inner PAN relays in the *macPANRelayList*, starts to join to the TRLE-enabled PAN coordinator, and replicates the beacon frame of the TRLE-enabled PAN coordinator until finishing the joining process. If the PAN relay fails to find the adjacent inner PAN relay, the PAN relay starts to search any neighbored inner PAN relay, as described in S.4.3.

If the PAN relay misses the beacon frame of the adjacent outer PAN relay for $macBeaconMissingLimit \times BI$, the PAN relay checks the status of the adjacent outer PAN relay by sending the TRLE-Management request command with the Management Type field set to Hello. If there is no response, the PAN relay makes the adjacent outer PAN relay leave the TRLE-enabled PAN by sending the TRLE-Management request command with the Management Type field set to Leave and the source address set to address of the adjacent outer PAN relay.

S.4.6 Multiple grades of link access

In a TRLE-enabled PAN, in order to accommodate various qualities of service requirements for relaying frames between the TRLE-enabled PAN coordinator and a TRLE PAN relay, three grades of link access are provided: grade 0 for delay sensitive data transmission, grade 1 for reliable data transmission, and grade 2 for best effort data transmission.

For grade 0 link access, to send a frame inward, a device shall wait until the earliest prioritized device time slot. If the device fails to transmit the data in the prioritized device time slot, the device will continue trying to transmit the data in the next prioritized device time slot. To send a frame outward, a device shall use the earliest coordinator time slot.

For grade 1 link access, a device shall wait until the earliest bidirectional time slot assigned to the device and transmit the data. If the device fails to transmit the data, the device will keep searching for the next available bidirectional time slot for the duration of the cyclic-superframe or will search the next cyclic-superframe for an opportunity to transmit the data.

For grade 2 link access, a device shall wait until the earliest bidirectional time slot assigned to the device and transmit the data without requiring an acknowledgment.

A frame with grade 0 or grade 1 link access shall be acknowledged hop-by-hop and end-to-end. At a TRLE PAN relay, if the Grade of Link Access field of the TRLE Descriptor IE is set to 0b00 or 0b01, the Frame Type field indicates a data or MAC command frame relayed inward, and the AR field is set to request an acknowledgment, the MAC sublayer shall send an acknowledgment frame within the same time slot in which the frame is received. If it fails to complete transmission of the acknowledgment frame before the end of the time slot, the acknowledgment frame shall be sent in the coordinator time slot of the following superframe.

S.5 MAC services for the TRLE-enabled PAN

S.5.1 TRLE information elements

S.5.1.1 TRLE Descriptor IE

The TRLE Descriptor IE shall be included in enhanced beacon, data, acknowledgment, and MAC command frames that are sent in a TRLE-enabled PAN.

The TRLE Descriptor IE shall be formatted as illustrated in Figure S.6.

Bits: 0 –2	3	4–5	6–9	10–23	Octets: 2
Relaying Tier Identifier	Relaying Direction	Grade of Link Access	Slot ID	Superframe ID	PAN Relay Address

Figure S.6—TRLE Descriptor format

The Relaying Tier Identifier field shall be set to the identifier of the relaying tier of the TRLE PAN relay by which this frame will be transmitted. A value of zero shall indicate tier 0 where the TRLE-enabled PAN coordinator is located.

The Relaying Direction field shall be set to one if the frame is relayed outward. Otherwise it is set to zero.

The Grade of Link access field shall be set to the TxGrade parameter stated in the primitive, as defined in S.5.3.

The Slot ID field contains the ID of the time slot in which this frame will be transmitted.

The Superframe ID field contains the ID of the superframe in which this frame will be transmitted.

The PAN Relay Address field of an inward frame or a beacon frame shall be set to the PIB attribute *macShortAddress* of the TRLE PAN relay by which this frame will be transmitted. The PAN Relay Address field of an outward frame, with the exception of a beacon frame, shall be set to one of the neighboring PAN relays in the *macPANRelayList*, indexed by the destination address of the MHR fields.

S.5.2 TRLE commands

S.5.2.1 TRLE-Management request command

The TRLE-Management request command allows a device with its PIB attribute *macTRLEenabled* set to TRUE to request to join a TRLE relaying path, leave the TRLE relaying path, report relaying path information, or assign a device slot.

Only devices with a 16-bit short address less than 0xfffe shall send this command.

The TRLE-Management request command shall be formatted as illustrated in Figure S.7.

Octets: variable	1	1	0/6	0/variable	0/1	0/variable
MHR fields (5.2.2.4.1)	Command Frame Identifier (Table 5)	Management Type (Table S.1)	Timestamp	Beacon Bitmap	Number of Slots	Relaying Path List

Figure S.7—TRLE-Management request command format

S.5.2.1.1 MHR fields

The Destination Addressing Mode and the Source Addressing Mode fields of the Frame Control field shall both be set to two (i.e., 16-bit short addressing).

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

The Source PAN Identifier field shall contain the value of *macPANId*, and the Source Address field shall contain the value of *macShortAddress*.

The Destination PAN Identifier field shall contain the value of *macPANId*, and the Destination Address field shall be set to the short address of the destination device.

S.5.2.1.2 Management Type field

The Management Type field shall be set as one of the values listed in Table S.1.

Table S.1—Values of the Management Type field

Management Type value	Description
0x00	Join
0x01	Leave
0x02	Hello
0x03	Path
0x04–0xff	Reserved

S.5.2.1.3 Timestamp field

This field is valid only if the value of the Management Type field is 0x02 (i.e., Hello) or 0x03 (i.e., Path).

The Timestamp field shall contain the time, in microseconds, of the time slot in which the TRLE-Management request command frame will be transmitted.

S.5.2.1.4 Beacon Bitmap field

This field is valid only if the value of the Management Type field is 0x00 (i.e., Join).

The Beacon Bitmap field is described in 5.2.4.9.3. The Beacon Bitmap field shall be set to the BeaconBitmap parameter of the MLME-TRLE-MANAGEMENT.request primitive.

S.5.2.1.5 Number of Slots field

This field is valid only if the value of the Management Type field is set to 0x00 (i.e., Join).

The Number of Slots field shall contain the number of bidirectional device time slots that this command is requesting. The Number of Slots field shall be set to the NumBidirectionalDeviceSlot parameter of the MLME-TRLE-MANAGEMENT.request primitive.

S.5.2.1.6 Relaying Path List field

This field is valid only if the value of the Management Type field is set to 0x00 (i.e., Join).

The Relaying Path List field shall be formatted as illustrated in Figure S.8.

The PAN Relay List Count field shall contain the number of the PAN relays in the PAN Relay List field.

The PAN Relay List field shall contain the TRLE descriptors on a TRLE path, as defined in S.5.1.1.

Octet: 1	variable
PAN Relay List Count	PAN Relay List

Figure S.8—TRLE Relaying Path Descriptor field format

S.5.2.2 TRLE-Management response command

The TRLE-Management response command allows the TRLE-enabled PAN coordinator or the TRLE PAN relay to communicate the results of a request to join a TRLE relaying path, leave the TRLE relaying path, report relaying path information, or assign a device slot.

Only devices with a 16-bit short address less than 0xfffe shall send this command.

The TRLE-Management response command shall be formatted as illustrated in Figure S.9.

Octets: variable	1	1	1	0/6	0/2	. . .	0/variable	0/variable	0/variable
MHR fields (5.2.2.4.1)	Command Frame Identifier (Table 5)	Management Type (Table S.1)	Management Status	Timestamp	Sync Relaying Offset	. . .	Bidirectional Device Slot List	Device Descriptor	Relaying Path List (S.5.2.1.6)

Figure S.9—TRLE-Management response command format

S.5.2.2.1 MHR fields

The Destination Addressing Mode and the Source Addressing Mode fields of the Frame Control field shall both be set to two (i.e., 16-bit short addressing).

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

The Source PAN Identifier field shall contain the value of *macPANId*, and the Source Address field shall contain the value of *macShortAddress*.

The Destination PAN Identifier field shall contain the value of *macPANId*, and the Destination Address field shall be set to the short address of the destination device.

S.5.2.2.2 Management Type field

The Management Type field is described in S.5.2.1.2.

S.5.2.2.3 Management Status field

The Management Status field shall be set to the status parameter of the MLME-TRLE-MANAGEMENT.response primitive.

S.5.2.2.4 Timestamp field

This field is valid only if the Management Type field is set to 0x00 (i.e., Join).

The Timestamp field shall contain the time, in microseconds, of the time slot in which the TRLE-Management response command frame will be transmitted.

S.5.2.2.5 Sync Relaying Offset field

This field is valid only if the Management Type field is set to 0x00 (i.e., Join).

The Sync Relaying Offset field shall contain the relaying delay of the cyclic-superframe of a PAN relay compared to the cyclic-superframe of the TRLE-enabled PAN coordinator, which is specified in the number of superframe duration.

The Sync Relaying Offset field shall be set to the SyncRelayingOffset parameter of the MLME-TRLE-MANAGEMENT.response primitive.

S.5.2.2.6 Bidirectional Device Slot List field

This field is valid only if the ManagementType field is set to 0x00 (i.e., Join).

The Bidirectional Device Slot List field shall be set to the BidirectionalDeviceSlotList parameter of the MLME-TRLE-MANAGEMENT.response primitive, as defined in S.5.3.3.

The Bidirectional Device Slot List field shall be formatted as illustrated in Figure S.10.

Octets: 1	variable
Bidirectional Device Slot List Count	Bidirectional Device Slot

Figure S.10—Bidirectional Device Slot List field format

The Bidirectional Device Slot List Count field shall contain the number of the Bidirectional Device Slot Descriptor in the Bidirectional Device Slot List field.

The Bidirectional Device Slot field shall be formatted as illustrated in Figure S.11.

Octets: 1	2
Slot ID	Superframe ID

Figure S.11—Bidirectional Device Slot Descriptor format

The Slot ID field contains the ID of the time slot of the superframe in which a bidirectional device time slot is assigned. The slot ID is the sequence number of the time slot in a superframe beginning from zero.

The Superframe ID field contains the ID of the superframe in which a bidirectional device time slot is assigned. The superframe ID is the sequence number of the superframe in a cyclic-superframe beginning from zero.

S.5.2.2.7 Device Descriptor field

This field is valid only if the Management Type field is set to 0x02 (i.e., Hello) or 0x03 (i.e., Path).

The Device Descriptor field shall be set to the DeviceDescriptor parameter of the MLME-TRLE-MANAGEMENT.response primitive, as described in S.5.3.3.

The Device Descriptor field shall be formatted as illustrated in Figure S.12.

Octets: 2	1	2	2	2	3	variable
Device Address	Relaying Tier Identifier	Sync Relaying Offset	Inner PAN Relay Address	Inner Relaying Offset	Primary Device Slot Descriptor	Beacon Bitmap (5.2.4.9.3)

Figure S.12—TRLE Device Descriptor format

The Device Address field shall be set to the short address of the TRLE device that this command is requesting.

The Relaying Tier Identifier field shall contain the identifier of relaying tier of the TRLE device that this command is requesting.

The Sync Relaying Offset field shall contain the relaying delay of the TRLE device that this command is requesting.

The Inner PAN Relay Address field shall be set to the short address of the inner PAN relay of the TRLE device that this command is requesting.

The Inner Relaying Offset field shall contain the relaying delay of the inner PAN relay of the TRLE device that this command is requesting.

The Primary Device Slot Descriptor field shall contain the primary bidirectional device slot of the TRLE device that this command is requesting and shall be formatted as illustrated in Figure S.11.

The Beacon Bitmap field is described in 5.2.4.9.3.

S.5.2.2.8 Relaying Path List field

This field is valid only if the Management Type field is set to 0x03 (i.e., Path).

The Relaying Path List field is described in S.5.2.1.6.

S.5.3 Primitives for managing the TRLE-enabled PAN

S.5.3.1 MLME-TRLE-MANAGEMENT.request

The MLME-TRLE-MANAGEMENT.request primitive requests to either start a TRLE-enabled PAN, join a TRLE relaying path, leave the TRLE relaying path, or report relaying path information.

The semantics of this primitive are:

```
MLME-TRLE-MANAGEMENT.request    (
                                ManagementType,
                                DstAddrMode,
                                DstAddr,
                                TxGrade,
                                NumPrioritizedDeviceSlot,
                                NumCoordSlot,
                                NumBidirectionalDeviceSlot,
                                SrcRelayingTier,
                                BeaconBitmap,
                                InnerRelayingOffset,
                                SyncRelayingOffset,
                                SecurityLevel,
                                KeyIdMode,
                                KeySource,
                                KeyIndex
                                )
```

The primitive parameters are defined in Table S.2.

Table S.2—MLME-TRLE-MANAGEMENT.request parameters

Name	Type	Valid range	Description
ManagementType	Enumeration	START, JOIN, LEAVE, RELAY_ON, RELAY_OFF, HELLO, PATH	The type of TRLE-enabled PAN management to be performed: START = 0, JOIN = 1, LEAVE = 2, RELAY_ON = 3, RELAY_OFF = 4, HELLO = 5, PATH = 6.
DstAddrMode	Enumeration	NO_ADDRESS, SHORT_ADDRESS, EXTENDED_ADDRESS	The destination addressing mode for this primitive.
DstAddr	Device address	As specified by DstAddrMode parameter	The individual device address of the device for which the frame was intended.
TxGrade	Enumeration	GRADE_0, GRADE_1, GRADE_2	The grade of link access to be used: GRADE_0 = 0, GRADE_1 = 1, GRADE_2 = 2.
NumPrioritizedDevice	Integer	1–6	The number of time slots in a superframe assigned as the prioritized device slots.
NumCoordSlot	Integer	1–6	The number of time slots in a superframe assigned as the coordinator slots.
NumBidirectional-DeviceSlot	Integer	0–5	The number of time slots in a cyclic-superframe assigned as the bidirectional device slot.
SrcRelayingTier	Integer	0–7	The identifier of the relaying tier in which a device is placed. The relaying tier of the PAN coordinator is zero.

Table S.2—MLME-TRLE-MANAGEMENT.request parameters *(continued)*

Name	Type	Valid range	Description
BeaconBitmap	Bitmap	As defined in 5.2.4.9.3	The beacon bitmap as specified in the received enhanced beacon frame.
InnerRelayingOffset	Integer	0x0000–0x7fff	The index of the superframe at which the inner PAN relay starts a cyclic-superframe. If the inner PAN relay of a device is the TRLE-enabled PAN coordinator, the InnerRelayingOffset of the device is zero.
SyncRelayingOffset	Integer	0x0000–0x7fff	The index of the superframe at which a device starts a cyclic-superframe. The SyncRelayingOffset of the PAN coordinator is zero.
SecurityLevel	Integer	As defined in Table 46	As defined in Table 46
KeyIdMode	Integer	As defined in Table 46	As defined in Table 46
KeySource	Set of octets	As defined in Table 46	As defined in Table 46
KeyIndex	Integer	As defined in Table 46	As defined in Table 46

The MLME-TRLE-MANAGEMENT.request primitive may be used by the TRLE-enabled PAN management layer to establish, operate, or maintain a TRLE relaying path.

When the ManagementType parameter is set to START, all parameters except NumPrioritizedDevice and NumCoordSlot shall be ignored, and the MAC sublayer shall attempt to update the cyclic-superframe specification and begin the transmission of the TRLE Relaying IE in an enhanced beacon.

When the ManagementType parameter is set to JOIN, all parameters except DstAddrMode, DstAddr, TxGrade, SrcRelayingTier, InnerRelayingOffset, BeaconBitmap, and NumBidirectionalDeviceSlot shall be ignored. The MAC sublayer shall attempt to update the appropriate MAC PIB attributes, as described in S.4.3, and generate a TRLE-Management request command with the Management Type field set to Join, as defined in S.5.2.1.

When the ManagementType parameter is set to LEAVE, all parameters except DstAddrMode, DstAddr, and TxGrade shall be ignored, and the MAC sublayer shall attempt to generate a TRLE-Management request command with the Management Type field set to Leave.

When the ManagementType parameter is set to RELAYING_ON, all parameters except NumPrioritizedDevice, NumCoordSlot, and SyncRelayingOffset shall be ignored, and the MAC sublayer shall begin relaying frames, as described in S.4.4.

When the ManagementType parameter is set to RELAYING_OFF, all parameters shall be ignored, and the MAC sublayer shall stop relaying frames.

When the ManagementType parameter is set to HELLO, all parameters except DstAddrMode and DstAddr shall be ignored, and the MAC sublayer shall attempt to generate a TRLE-Management request command with the Management Type field set to Hello.

When the ManagementType parameter is set to PATH, all parameters except DstAddrMode and DstAddr shall be ignored, and the MAC sublayer shall attempt to generate a TRLE-Management request command with the Management Type field set to Path.

The TRLE-Management request command frame is relayed to the DstAddr with the grade of link access specified in TxGrade.

Typically, the TRLE-Management request command should not be implemented using security. However, if the device shares a key with the coordinator, then security may be specified.

S.5.3.2 MLME-TRLE-MANAGEMENT.indication

The MLME-TRLE-MANAGEMENT.indication is used to indicate the reception of a TRLE-Management Request command.

The semantics of this primitive are:

```
MLME-TRLE-MANAGEMENT.indication   (
                                  ManagementType,
                                  SrcAddrMode,
                                  SrcAddr,
                                  TxGrade,
                                  Timestamp
                                  BeaconBitmap,
                                  NumBiDirectionalDeviceSlot,
                                  RelayingPathList,
                                  SecurityLevel,
                                  KeyIdMode,
                                  KeySource,
                                  KeyIndex
                                  )
```

The primitive parameters are defined in Table S.3.

Table S.3—MLME-TRLE-MANAGEMENT.indication parameters

Name	Type	Valid range	Description
ManagementType	Enumeration	START, JOIN, LEAVE, RELAY_ON, RELAY_OFF, HELLO, PATH	The type of TRLE-enabled PAN management to be performed: START = 0, JOIN = 1, LEAVE = 2, RELAY_ON = 3, RELAY_OFF = 4, HELLO = 5, PATH = 6.
SrcAddrMode	Enumeration	NO_ADDRESS, SHORT_ADDRESS, EXTENDED_ADDRESS	The source addressing mode for this primitive.
SrcAddr	Device address	As specified by SrcAddrMode parameter	The individual device address of the device for which the frame was generated.
TxGrade	Enumeration	GRADE_0, GRADE_1, GRADE_2	The grade of link access to be used: GRADE_0 = 0, GRADE_1 = 1, GRADE_2 = 2.

Table S.3—MLME-TRLE-MANAGEMENT.indication parameters *(continued)*

Name	Type	Valid range	Description
Timestamp	Integer	0x00 0000–0xff ffff	The time, in symbols, at which the TRLE-Management request command was transmitted. The symbol boundary is described by *macSyncSymbolOffset*, as defined in Table 52. 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.
BeaconBitmap	Bitmap	As defined in 5.2.4.9.3	The beacon bitmap as specified in the received enhanced beacon frame.
NumBidirectional-DeviceSlot	Integer	0–5	The number of time slots in a cyclic-superframe assigned as the bidirectional device slot.
RelayingPathList	Set of octets of variable length	As defined in S.5.2.1.6	The relaying information on a TRLE relaying path
SecurityLevel	Integer	As defined in Table 46	As defined in Table 46
KeyIdMode	Integer	As defined in Table 46	As defined in Table 46
KeySource	Set of octets	As defined in Table 46	As defined in Table 46
KeyIndex	Integer	As defined in Table 46	As defined in Table 46

This primitive is generated by the MLME of a device and issued to its next higher layer upon the reception of a TRLE-Management request command frame.

On receipt of the MLME-TRLE-MANAGEMENT.indication primitive, the next higher layer is notified of the reception of a TRLE-Management request command frame.

When the ManagementType parameter is set to JOIN, all parameters except SrcAddrMode, SrcAddr, TxGrade, BeaconBitmap, NumBidirectionalDeviceSlot, and RelayingPathList shall be ignored.

When the ManagementType parameter is set to LEAVE, all parameters except SrcAddrMode, SrcAddr, and TxGrade shall be ignored.

When the ManagementType parameter is set to HELLO, all parameters except SrcAddrMode, SrcAddr, TxGrade, and Timestamp shall be ignored.

When the ManagementType parameter is set to PATH, all parameters except SrcAddrMode, SrcAddr, TxGrade, and Timestamp shall be ignored.

S.5.3.3 MLME-TRLE-MANAGEMENT.response

This primitive allows the next higher layer of a device to respond to the MLME-TRLE-MANAGEMENT.indication primitive.

The semantics of this primitive are:

```
MLME-TRLE-MANAGEMENT.response      (
                                   ManagementType,
                                   DstAddrMode,
                                   DstAddr,
                                   TxGrade,
                                   status,
                                   NumPrioritizedDeviceSlot,
                                   NumCoordSlot,
                                   NumBidirectionalDeviceSlot,
                                   SyncRelayingOffset,
                                   BidirectionalDeviceSlotList,
                                   DeviceDescriptor,
                                   RelayingPathList,
                                   SecurityLevel,
                                   KeyIdMode,
                                   KeySource,
                                   KeyIndex
                                   )
```

The primitive parameters are defined in Table S.4.

Table S.4—MLME-TRLE-MANAGEMENT.response parameters

Name	Type	Valid range	Description
ManagementType	Enumeration	START, JOIN, LEAVE, RELAY_ON, RELAY_OFF, HELLO, PATH	The type of TRLE-enabled PAN management to be performed: START = 0, JOIN = 1, LEAVE = 2, RELAY_ON = 3, RELAY_OFF = 4, HELLO = 5, PATH = 6.
DstAddrMode	Enumeration	NO_ADDRESS, SHORT_ADDRESS, EXTENDED_ADDRESS	The destination addressing mode for this primitive.
DstAddr	Device address	As specified by DstAddrMode parameter	The individual device address of the device for which the frame was intended.
TxGrade	Enumeration	GRADE_0, GRADE_1, GRADE_2	The grade of link access to be used: GRADE_0 = 0, GRADE_1 = 1, GRADE_2 = 2.
status	Enumeration	As defined in S.5.3.4	The status of the management attempt.
NumPrioritizedDevice	Integer	1–6	The number of time slots in a superframe assigned as the prioritized device slots.
NumCoordSlot	Integer	1–6	The number of time slots in a superframe assigned as the coordinator slots.
NumBidirectional-DeviceSlot	Integer	0–5	The number of time slots in a cyclic-superframe assigned as the bidirectional device slot.

Table S.4—MLME-TRLE-MANAGEMENT.response parameters *(continued)*

Name	Type	Valid range	Description
SyncRelayingOffset	Integer	0x0000–0x7fff	The index of the superframe at which a device starts a cyclic-superframe. The SyncRelayingOffset of the PAN coordinator is zero.
BidirectionalDeviceSlotList	Set of octets of variable length	As described in S.5.2.2.6	The set of bidirectional device time slots to be allocated for the device.
DeviceDescriptor	Set of octets	As defined in S.5.2.2.7	The relaying specification of a device.
RelayingPathList	Set of octets of variable length	As defined in S.5.2.1.6	The relaying information on a TRLE relaying path.
SecurityLevel	Integer	As defined in Table 46	As defined in Table 46
KeyIdMode	Integer	As defined in Table 46	As defined in Table 46
KeySource	Set of octets	As defined in Table 46	As defined in Table 46
KeyIndex	Integer	As defined in Table 46	As defined in Table 46

On receipt of the MLME-TRLE-MANAGEMENT.response primitive, the MLME of the device shall generate a TRLE-Management response command frame.

When the ManagementType parameter is set to JOIN, all parameters except DstAddrMode, DstAddr, TxGrade, status, NumPrioritizedDeviceSlot, NumCoordSlot, SyncRelayingOffset, NumBidirectionalDeviceSlot, and BidirectionalDeviceSlotList shall be ignored. The MAC sublayer shall generate a TRLE-Management response command with the Management Type field set to Join, as defined in S.5.2.2.

When the ManagementType parameter is set to LEAVE, all parameters except DstAddrMode, DstAddr, TxGrade, and status shall be ignored, and the MAC sublayer shall generate a TRLE-Management response command with the Management Type field set to Leave.

When the ManagementType parameter is set to HELLO, all parameters except DstAddrMode, DstAddr, TxGrade, status, and DeviceDescriptor shall be ignored. The MAC sublayer shall generate a TRLE-Management response command with Management Type field set to Hello.

When the ManagementType parameter is set to PATH, all parameters except DstAddrMode, DstAddr, TxGrade, status, and DeviceDescriptor shall be ignored. The MAC sublayer shall generate a TRLE-Management response command with the Management Type field set to Path.

S.5.3.4 MLME-TRLE-MANAGEMENT.confirm

The MLME-TRLE-MANAGEMENT.confirm primitive reports the result of the TRLE management request.

The semantics of this primitive are:

```
MLME-TRLE-MANAGEMENT.confirm    (
                                ManagementType,
                                SrcAddrMode,
                                SrcAddr,
                                status,
                                Timestamp,
                                NumPrioritizedDeviceSlot,
                                NumCoordSlot,
                                SyncRelayingOffset,
                                NumBidirectionalDeviceSlot,
                                BidirectionalDeviceSlotList,
                                DeviceDescriptor,
                                RelayingPathList,
                                SecurityLevel,
                                KeyIdMode,
                                KeySource,
                                KeyIndex
                                )
```

The primitive parameters are defined in Table S.5.

Table S.5—MLME-TRLE-MANAGEMENT.confirm parameters

Name	Type	Valid range	Description
ManagementType	Enumeration	START, JOIN, LEAVE, RELAY_ON, RELAY_OFF, HELLO, PATH	The type of TRLE-enabled PAN management to be performed: START = 0, JOIN = 1, LEAVE = 2, RELAY_ON = 3, RELAY_OFF = 4, HELLO = 5, PATH = 6.
SrcAddrMode	Enumeration	NO_ADDRESS, SHORT_ADDRESS, EXTENDED_ADDRESS	The source addressing mode for this primitive.
SrcAddr	Device address	As specified by SrcAddrMode parameter	The individual device address of the device for which the frame was generated.
status	Enumeration	SUCCESS, INVALID_PARAMETER, CHANNEL_ACCESS_FAILURE, FRAME_TOO_LONG, SLOT_FULL, RELAY_FULL, NOT_FOUND, NOT_CONFIRMED, UNAVAILABLE_KEY, UNSUPPORTED_SECURITY	The result of the management request attempt.

Table S.5—MLME-TRLE-MANAGEMENT.confirm parameters *(continued)*

Name	Type	Valid range	Description
Timestamp	Integer	0x00 0000–0xff ffff	The time, in symbols, at which the TRLE-Management request command was transmitted. The symbol boundary is described by *macSyncSymbolOffset*, as defined in Table 52. 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.
NumPrioritizedDevice	Integer	1–6	The number of time slots in a superframe assigned as the prioritized device slots.
NumCoordSlot	Integer	1–6	The number of time slots in a superframe assigned as the coordinator slots.
NumBidirectional-DeviceSlot	Integer	0–5	The number of time slots in a cyclic-superframe assigned as the bidirectional device slot.
SyncRelayingOffset	Integer	0x0000–0x7fff	The index of the superframe at which a device starts a cyclic-superframe. The SyncRelayingOffset of the PAN coordinator is zero.
BidirectionalDeviceSlotList	Set of octets of variable length	As defined in S.5.2.2.6	The set of bidirectional device time slots to be allocated for the device.
DeviceDescriptor	Set of octets	As defined in S.5.2.2.7	The relaying specification of a device.
RelayingPathList	Set of octets of variable length	As defined in S.5.2.1.6	The relaying information on a TRLE relaying path.
SecurityLevel	Integer	As defined in Table 46 or Table 48	If the primitive was generated following the failed outgoing processing of a TRLE-Management request command, then it is as defined in Table 46. If the primitive was generated following the receipt of a TRLE-Management response command, then it is as defined in Table 48.
KeyIdMode	Integer	As defined in Table 46 or Table 48	If the primitive was generated following the failed outgoing processing of a TRLE-Management request command, then it is as defined in Table 46. If the primitive was generated following the receipt of a TRLE-Management response command, then it is as defined in Table 48.

Table S.5—MLME-TRLE-MANAGEMENT.confirm parameters *(continued)*

Name	Type	Valid range	Description
KeySource	Set of octets	As defined in Table 46 or Table 48	If the primitive was generated following the failed outgoing processing of a TRLE-Management request command, then it is as defined in Table 46. If the primitive was generated following the receipt of a TRLE-Management response command, then it is as defined in Table 48.
KeyIndex	Integer	As defined in Table 46 or Table 48	If the primitive was generated following the failed outgoing processing of a TRLE-Management request command, then it is as defined in Table 46. If the primitive was generated following the receipt of a TRLE-Management response command, then it is as defined in Table 48.

The MLME-TRLE-MANAGEMENT.confirm primitive with the ManagementType parameter set to START, RELAY_ON, or RELAY_OFF is generated by the MAC sublayer entity in response to an MLME-TRLE-MANAGEMENT.request primitive.

When the ManagementType parameter is set to START, RELAY_ON, or RELAY_OFF, all parameters except the status parameter shall be ignored.

On receipt of the MLME-TRLE-MANAGEMENT.confirm primitive with the ManagementType parameter set to JOIN, LEAVE, HELLO, or PATH, the next higher layer is notified of the reception of a TRLE-Management response command frame.

When the ManagementType parameter is set to JOIN, all parameters except SrcAddrMode, SrcAddr, status, NumPrioritizedDeviceSlot, NumCoordSlot, SyncRelayingOffset, NumBidirectionalDeviceSlot, and BidirectionalDeviceSlotList shall be ignored.

When the ManagementType parameter is set to LEAVE, all parameters except SrcAddrMode, SrcAddr, and status shall be ignored.

When the ManagementType parameter is set to HELLO, all parameters except SrcAddrMode, SrcAddr, status, and DeviceDescriptor shall be ignored.

When the ManagementType parameter is set to PATH, all parameters except SrcAddrMode, SrcAddr, status, DeviceDescriptor, and RelayingPathList shall be ignored.

The MLME-TRLE-MANAGEMENT.confirm primitive returns a status of either SUCCESS or the appropriate error code:

- CHANNEL_ACCESS_FAILURE indicates that the transmission of the coordinator realignment frame failed.
- FRAME_TOO_LONG indicates that the length of the beacon frame exceeds *aMaxPHYPacketSize*.
- SLOT_FULL indicates that the allocation of the bidirectional device time slot failed.
- RELAY_FULL indicates that the allocation of the superframe for relaying a beacon failed.

— NOT_FOUND indicates that the requesting device cannot be found.
— NOT_CONFIRMED indicates that the request to leave a relaying path is not permitted.
— A security error code, as defined in 7.2.

S.5.4 TRLE specific MAC PIB attributes

The attributes contained in the MAC PIB for TRLE are presented in Table S.6.

Table S.6—TRLE specific MAC PIB attributes

Attribute	Type	Range	Description	Default
macNumPrioritizedDeviceSlot	Integer	1–6	The number of time slots in a superframe assigned as the prioritized device slots.	3
macNumCoordSlot	Integer	1–6	The number of time slots in a superframe assigned as the coordinator slots.	3
macNumBidirectionalDeviceSlot	Integer	0–5	The number of time slots in a cyclic-superframe assigned as the bidirectional device slots.	1
macRelayingTier	Integer	0–7	The identifier of the relaying tier in which a device is placed. The relaying tier of the PAN coordinator is zero.	Implementation specific
macInnerRelayingOffset	Integer	0x0000–0x7fff	The relaying delay of the cyclic-superframe of an inner PAN relay compared with the cyclic-superframe of a TRLE-enabled PAN coordinator, which is specified in the number of superframe duration. If the inner PAN relay of a device is the TRLE-enabled PAN coordinator, the value of *macInnerRelayingOffset* of the device is zero.	Implementation specific
macSyncRelayingOffset	Integer	0x0000–0x7fff	The relaying delay of the cyclic-superframe of a PAN relay compared with the cyclic-superframe of the TRLE-enabled PAN coordinator, which is specified in the number of superframe duration. The value of *macSyncRelayingOffset* of the PAN coordinator is zero.	Implementation specific
macPANRelayList	PAN relay list	PAN relay list	The list of the neighboring PAN relays, which inform the end devices reached by the PAN relay.	Implementation specific
macBeaconMissingLimit	Integer	0–7	The number of beacons that are missed before starting link recovery processing.	Implementation specific