IEEE Standard for Local and metropolitan area networks—

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

Amendment 2: Active Radio Frequency Identification (RFID) System Physical Layer (PHY)

IEEE Computer Society

Sponsored by the
LAN/MAN Standards Committee

IEEE
3 Park Avenue
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USA

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(Amendment to
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Approved 6 February 2012

IEEE-SA Standards Board

Abstract: This amendment provides two PHYs (MSK and LRP UWB) that can be used in a wide range of applications requiring various combinations of low cost, low energy consumption, multi-year battery life, reliable communications, precision location, and reader options. This PHY standard supports the performance and flexibility needed for future mass deployments of highly populated autonomous active RFID systems anywhere in the world.

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

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Introduction

This introduction is not part of IEEE Std 802.15.4f-2012, IEEE Standard for Local and metropolitan area networks—Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)—Amendment 2: Active Radio Frequency Identification (RFID) System Physical Layer (PHY).

This amendment specifies two alternate PHYs (MSK and LRP UWB) 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.

The alternate PHYs support principally low cost, low energy consumption, multi-year battery life, reliable communications, precision location, and sensor applications under multiple regulatory domains. The PHYs are as follows:

— MSK PHY
— Low rate PRF UWB PHY

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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.[1]

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

1. Overview

1.2 Scope

Change the first item of the dashed list as follows:

— Devices operating in the license-free 433.05 MHz to 434.79 MHz, 868 MHz to 868.6 MHz, 902 MHz to 928 MHz, ~~and~~ 2400 MHz to 2483.5 MHz, and 6289.6 MHz to 9185.6 MHz bands

1.3 Purpose

Change the second and third paragraphs as follows:

In addition, ~~one of the~~ alternate PHYs provide~~s~~ precision ranging ~~capability~~ capabilities that ~~is~~ are accurate to one meter.

Multiple PHYs are defined to support a variety of frequency bands including

— 433.05 MHz to 434.79 MHz (worldwide, varies by region)
— 868 MHz to 868.6 MHz
— 902 MHz to 928 MHz
— 2400 MHz to 2483.5 MHz
— 6289.6 MHz to 9185.6 MHz
— 314 MHz to 316 MHz, 430 MHz to 434 MHz, and 779 MHz to 787 MHz band for LR-WPAN systems in China
— 950 MHz to 956 MHz in Japan

3. Definitions, acronyms, and abbreviations

3.1 Definitions

Insert the following items in alphabetical order:

active radio frequency identification (RFID): The use of an electromagnetic radio signal, not derived from electromagnetic or inductive coupling, to communicate to or from a device through a variety of modulation and encoding schemes in order to uniquely read the identity of the device. To generate the radio signal, these devices must employ some source of power such as integrated batteries or harvesting of ambient energy from the surrounding environment.

active radio frequency identification (RFID) tag: A device that may be attached to an asset that transmits a periodic radio emission for the purpose of asset identification and/or location**.**

location enhancing information postamble (LEIP): An optional set of bits added after the completion of a frame that are used to enhance the ability to locate the transmitter.

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

reader: A device that receives signals from active radio frequency identification (RFID) or real time locating system (RTLS) transmitters.

real time locating system: A set of radio frequency receivers and associated computing equipment used to determine the position of a transmitting device relative to the placement of the aforementioned receivers.

3.2 Acronyms and abbreviations

Insert the following items in alphabetical order:

CPFSK continuous phase frequency shift keying

LEIP location enhancing information postamble

LRP low rate pulse repetition frequency (PRF)

MSK minimum shift keying

OOK on-off keying

RFD-RX reduced function device—receive only

RFD-TX reduced function device—transmit only

RFID radio frequency identification

RTLS real time locating system

4. General description

4.1 General

Change the last paragraph as follows:

Two different device types can participate in an IEEE 802.15.4 network; a full-function device (FFD) and a reduced function device (RFD). The FFD is a device that is capable of serving as a personal area network (PAN) coordinator or a coordinator. An RFD is a device that is not capable of serving as either a PAN coordinator or a coordinator. An RFD is intended for applications that are extremely simple, such as a light switch or a passive infrared sensor; it does not have the need to send large amounts of data and only associates with a single FFD at a time. Consequently, the RFD can be implemented using minimal resources and memory capacity, and serve as a RFD-TX or RFD-RX device.

4.2 Components of the IEEE 802.15.4 WPAN

Change the first paragraph as follows:

A system conforming to this standard consists of several components. The most basic is the device. Two or more devices communicating on the same physical channel constitute a WPAN. However, this WPAN includes at least one FFD~~, which operates as the PAN coordinator.~~ operating as the PAN coordinator or at least one RFD-RX operating as the termination point for RFD-TX communications.

4.3 Network topologies

Change the first paragraph as follows:

Depending on the application requirements, an IEEE 802.15.4 LR-WPAN operates in either of two topologies: the star topology or the peer-to-peer topology. Both are shown in Figure 1. In the star topology the communication is established between devices and a single central controller, called the PAN coordinator. A device typically has some associated application and is either the initiation point or the termination point for network communications. A PAN coordinator can also have a specific application, but it can be used to initiate, terminate, or route communication around the network. The PAN coordinator is the primary controller of the PAN. All devices operating on a network of either topology have unique addresses, referred to as extended addresses. A device will use either the extended address for direct communication within the PAN or the short address that was allocated by the PAN coordinator when the device associated. The transmission of the extended and short address fields is optional for RFD-TX devices. The PAN coordinator will often be mains powered, while the devices will most likely be battery powered. Applications that benefit from a star topology include home automation, personal computer (PC) peripherals, games, and personal health care.

4.3.1 Star network formation

Change the first paragraph as follows:

The basic structure of a star network is illustrated in Figure 1. After an FFD is activated, it can establish its own network and become the PAN coordinator. All star networks operate independently from all other star networks currently in operation. This is achieved by choosing a PAN identifier that is not currently used by any other network within the radio communications range. Once the PAN identifier is chosen, the PAN coordinator allows other devices, potentially both FFDs and RFDs, to join its network. The higher layer can use the procedures described in 5.1.2 and 5.1.3 to form a star network. An RFD-RX may also serve as a PAN coordinator termination point for RFD-TXs using the ALOHA mechanism as described in 8.2.7.

4.4 Architecture

4.4.1 Physical layer (PHY)

Change the last paragraph as follows:

A discussion of the coexistence of the various IEEE 802.15.4 PHYs with other wireless systems is given in "Coexistence analysis of IEEE Std 802.15.4 with other IEEE standards and proposed standards" [B4] and "TG4f Coexistence Assurance Document" [B22].

5. MAC protocol

5.1 MAC functional description

Change the second paragraph as follows:

There are two device types: a full-function device (FFD) and a reduced-function device (RFD). The FFD may operate in three modes serving as a personal area network (PAN) coordinator, a coordinator, or a device. An RFD shall only operate as a device, RFD-TX device, or RFD-RX device.

5.1.2 Starting and maintaining PANs

5.1.2.1 Scanning through channels

Change the first paragraph as follows:

All devices, except for the RFD-RX and RFD-TX devices, shall be capable of performing passive and orphan scans across a specified list of channels. In addition, an FFD shall be able to perform energy detection (ED) and active scans. The next higher layer should submit a scan request for a particular channel page containing a list of channels chosen only from the channels specified by *phyChannelsSupported* for that particular channel page.

5.1.2.1.2 Active and passive channel scan

Change the fifth paragraph as follows:

If a beacon frame is received when *macAutoRequest* is set to TRUE, the list of PAN descriptor structures shall be stored by the MAC sublayer until the scan is complete; at this time, the list shall be sent to the next higher layer in the PANDescriptorList parameter of the MLME-SCAN.confirm primitive. A device, optional for RFD-RX and RFD-TX devices, shall be able to store at least one PAN descriptor. A beacon frame shall be assumed to be unique if it contains both a PAN identifier and a source address that has not been seen before during the scan of the current channel.

5.1.3 Association and disassociation

5.1.3.1 Association

Change the text as follows:

The MAC sublayer of an unassociated device shall initiate the association procedure by sending an association request command, as described in 5.3.1, to the coordinator of an existing PAN~~;~~. This is optional for RFD-RX and RFD-TX devices.~~; i~~If the association request command cannot be sent due to a channel access failure, the MAC sublayer shall notify the next higher layer.

On receipt of the acknowledgment to the association request command, the device shall wait for at most *macResponseWaitTime* for the coordinator to make its association decision; the PIB attribute *macResponseWaitTime* is a network-topology-dependent parameter and may be set to match the specific requirements of the network that a device is trying to join. If the device is tracking the beacon, it shall attempt to extract the association response command from the coordinator whenever it is indicated in the beacon frame. If the device is not tracking the beacon, it shall attempt to extract the association response command from the coordinator after *macResponseWaitTime*. If the device, optional for RFD-RX and RFD-TX devices, does not extract an association response command frame from the coordinator within *macResponseWaitTime*, the MLME shall issue the MLME-ASSOCIATE.confirm primitive, as described in 6.2.2.4, with a status of NO_DATA, and the association attempt shall be deemed a failure. In this case, the next higher layer shall terminate any tracking of the beacon. This is achieved by issuing the MLME-SYNC.request primitive, as described in 6.2.13.1, with the TrackBeacon parameter set to FALSE.

If the value of the Association Status field of the command is not "Association successful," if there were a communication failure during the association process due to a missed acknowledgment, or if the association response command frame were not received, the device, optional for RFD-RX and RFD-TX devices, shall set *macPANId* to the default value (0xffff).

5.1.4 Synchronization

5.1.4.2 Synchronization without beacons

Change the first paragraph as follows:

All devices, except for RFD-RX and RFD-TX devices, operating on a nonbeacon-enabled PAN (*macBeaconOrder* = 15) shall be able to poll the coordinator for data at the discretion of the next higher layer.

5.1.5 Transaction handling

Change the third paragraph as follows:

The information contained in the indirect transmission request forms a transaction, and except for RFD-RX devices serving as PAN coordinator termination points, the coordinator shall be capable of storing at least one transaction. On receipt of an indirect transmission request, if there is no capacity to store another transaction, the MAC sublayer shall indicate to the next higher layer a status of TRANSACTION_OVERFLOW in the appropriate corresponding primitive.

5.1.6 Transmission, reception, and acknowledgment

5.1.6.1 Transmission

Change the third paragraph as follows:

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

5.3 MAC command frames

5.3.1 Association request command

Change the third paragraph as follows:

All devices, except for RFD-RX and RFD-TX devices, shall be capable of transmitting this command, although an RFD is not required to be capable of receiving it.

5.3.2 Association response command

Change the third paragraph as follows:

All devices, except for RFD-RX and RFD-TX devices, shall be capable of receiving this command, although an RFD is not required to be capable of transmitting it.

5.3.3 Disassociation notification command

Change the second paragraph as follows:

All devices, except for RFD-RX and RFD-TX devices, shall implement this command.

5.3.4 Data request command

Change the third paragraph as follows:

All devices, except for RFD-TX devices, shall be capable of transmitting this command, although an RFD is not required to be capable of receiving it.

5.3.5 PAN ID conflict notification command

Change the second paragraph as follows:

All devices, except for RFD-RX and RFD-TX devices, shall be capable of transmitting this command, although an RFD is not required to be capable of receiving it.

5.3.6 Orphan notification command

Change the second paragraph as follows:

All devices, except for RFD-RX and RFD-TX devices, shall be capable of transmitting this command, although an RFD is not required to be capable of receiving it.

5.3.8 Coordinator realignment command

Change the third paragraph as follows:

All devices, except for RFD-RX and RFD-TX devices, shall be capable of receiving this command, although an RFD is not required to be capable of transmitting it.

6. MAC services

6.2 MAC management service

Change the first paragraph as follows:

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). Primitives marked with a square (■) are optional for both RFD-RX and RFD-TX device types. The primitives are discussed in the subclauses referenced in the table.

Change the following rows in Table 8 as shown:

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

Name	Request	Indication	Response	Confirm
MLME-ASSOCIATE	6.2.2.1■	6.2.2.2 ♦■	6.2.2.3♦■	6.2.2.4■
MLME-DISASSOCIATE	6.2.3.1■	6.2.3.2■		6.2.3.3■
MLME-BEACON-NOTIFY		6.2.4.1■		
MLME-GTS	6.2.6.1*■	6.2.6.3*■		6.2.6.2*■
MLME-ORPHAN		6.2.7.1♦■	6.2.7.2♦■	
MLME-SCAN	6.2.10.1■			6.2.10.2■
MLME-START	6.2.12.1♦■			6.2.12.2♦■
MLME-SYNC	6.2.13.1*■			
MLME-SYNC-LOSS		6.2.13.2■		
MLME-POLL	6.2.14.1■			6.2.14.2■
MLME-DPS	6.2.15.1*■	6.2.15.3*■		6.2.15.2*■
MLME-SOUNDING	6.2.16.2*■			6.2.16.2*■
MLME-CALIBRATE	6.2.17.1*■			6.2.17.1*■

6.2.16 Primitives for channel sounding

6.2.16.2 MLME-SOUNDING.confirm

Change Table 43 as shown:

Table 43—Elements of a SoundingList

Name	Type	Valid range	Description
SoundingTime	Signed integer	—	The LSB represents a nominal 16 ps (see NOTE).
SoundingAmplitude	Signed integer	—	A relative measurement or the received signal strength.
NOTE—Each element of the *SoundingList* contains a *SoundingTime* and a *SoundingAmplitude*. The *SoundingTime* is a signed integer, and the LSB for the UWB PHY represents a nominal 16 ps (2^{-7} of a chip time), and for the LRP UWB PHY 1ps (2^{-20} of a chip time). The *SoundingAmplitude* is a signed integer representing a relative measurement. The *SoundingAmplitudes* have no absolute meaning, only a relative meaning.			

6.2.17 Primitives for ranging calibration (for UWB PHYs)

6.2.17.1 MLME-CALIBRATE.confirm

Change the following rows in Table 44 as shown:

Table 44—MLME-CALIBRATE.confirm parameters

Name	Type	Valid range	Description
CalTxRMARKER Offset	Unsigned Integer	0x00000000–0xffffffff	~~A count of the propagation time from them ranging counter to the transmit antenna. The LSB of a time value represents 1/128 of a chip time at the mandatory chipping rate of 499.2 MHz.~~ A count of the propagation time from the ranging counter to the transmit antenna. For the UWB PHY the LSB of a time value represents 2^{-7} of a chip time at the mandatory chipping rate of 499.2 MHz. For the LRP UWB PHY the LSB of a time value represents 2^{-20} of the base mode chipping rate of 1 MHz.
CalRxRMARKER Offset	Unsigned Integer	0x00000000–0xffffffff	~~A count of the propagation time from the receive antenna to the ranging counter. The LSB of a time value represents 1/ 128 of a chip time at the mandatory chipping rate of 499.2 MHz.~~ A count of the propagation time from the receive antenna to the ranging counter. For the UWB PHY the LSB of a time value represents 2^{-7} of a chip time at the mandatory chipping rate of 499.2 MHz. For the LRP UWB PHY the LSB of a time value represents 2^{-20} of the base mode chipping rate of 1 MHz.

6.3 MAC data service

6.3.1 MCPS-DATA.request

Insert the following new parameters at the end of the list as shown:

```
MCPS-DATA.request        (
                         SrcAddrMode,
                         DstAddrMode,
                         DstPANId,
                         DstAddr,
                         msduLength,
                         msdu,
```


msduHandle,
AckTX,
GTSTX,
IndirectTX,
SecurityLevel,
KeyIdMode,
KeySource,
KeyIndex,
UWBPRF,
Ranging,
UWBPreambleSymbolRepetitions,
DataRate,
LocationEnhancingInformationPostamble,
LocationEnhancingInformationPostambleLength,
)

Change last two rows and insert two new rows at the end of Table 46 as shown:

Table 46—MCPS-DATA.request parameters

Name	Type	Valid range	Description
UWBPreamble-SymbolRepetitions	Integer	0, 16, 32, 64, 128, 256, 512, 1024, 4096, 8192	The preamble symbol repetitions of the UWB PHY or LRP UWB frame. A zero value is used for non-UWB PHYs. all other PHYs. (see NOTE)
DataRate	Integer	0–4	Indicates the data rate. For CSS PHYs, a value of 1 indicates 250 kb/s while a value of two indicates 1 Mb/s. For UWB PHYs, values 1–4 are valid and are defined in 14.2.6.1. For LRP UWB PHYs, values 1–3 are valid and are defined in Table 121. For MSK PHYs values 1–3 are valid and are defined in Table 116. For all other PHYs, the parameter is set to zero.
Location-EnhancingInfor-mationPostamble	Enumeration	LEIP_NONE, LEIP_IMMEDIATE, LEIP_DELAYED	For the LRP UWB PHY this parameter specifies whether the Location enhancing information postamble sequence is to be sent or not and, if present, whether it directly follows the CRC or is delayed by the aLeipDelayTime. A value of LEIP_NONE is used for non-LRP UWB PHYs.
Location-EnhancingInfor-mationPostamble-Length	Enumeration	LEIP_LEN_16, LEIP_LEN_64, LEIP_LEN_128, LEIP_LEN_192, LEIP_LEN_256, LEIP_LEN_512, LEIP_LEN_1024	For the LRP UWB PHY when the LocationEnhancingInformationPostamble parameter has a value of either LEIP_IMMEDIATE or LEIP_DELAYED, then this parameter specifies the length in pulses of the location enhancing information postamble to send. This parameter is ignored when the LocationEnablingInformationPostamble parameter has a value of LEIP_NONE.
NOTE—Some values may be unsupported or invalid depending on the capabilities of the PHY or its current transmission mode as selected by other parameters.			

6.3.2 MCPS-DATA.confirm

Change the following rows in Table 47 as shown:

Table 47—MCPS-DATA.confirm parameters

Name	Type	Valid range	Description
Ranging-CounterStart	Unsigned Integer	0x00000000–0xffffffff	A count of the time units corresponding to an RMARKER at the antenna at the beginning of a ranging exchange, as described in 14.7.1. A value of 0x00000000 is used if ranging is not supported, not enabled or if counter was not used for this PPDU. A value of 0x00000000 is also used when one-way ranging is being employed (see E.1.2).
Ranging-CounterStop	Unsigned Integer	0x00000000–0xffffffff	A count of the time units corresponding to an RMARKER at the antenna at the end of a ranging exchange, as described in 14.7.1. A value of 0x00000000 is used if ranging is not supported, not enabled, or if the counter is not used for this PPDU. For one-way ranging this parameter reports the arrival time of the RMARKER at the antenna. (One-way ranging is described in E.1.2.)
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, INVALID_PARAMETER, UNSUPPORTED_PRF, UNSUPPORTED_RANGING, UNSUPPORTED_PSR, UNSUPPORTED_DATARATE, UNSUPPORTED_LEIP	The status of the last MSDU transmission.

6.3.3 MCPS-DATA.indication

Insert the following new parameters at the end of the list as shown:

```
MCPS-DATA.indication    (
                        SrcAddrMode,
                        SrcPANId,
                        SrcAddr,
                        DstAddrMode,
                        DstPANId
                        DstAddr,
                        msduLength,
```

msdu,
mpduLinkQuality,
DSN,
Timestamp,
SecurityLevel,
KeyIdMode,
KeySource,
KeyIndex,
UWBPRF,
UWBPreambleSymbolRepetitions,
DataRate,
RangingReceived,
RangingCounterStart,
RangingCounterStop,
RangingTrackingInterval,
RangingOffset,
RangingFOM,
AngleOfArrivalAzimuth,
AngleOfArrivalElevation,
AngleOfArrivalSupported,
RSSI
)

Insert the following new rows at the end of Table 48:

Table 48—MCPS-DATA.indication parameters

Name	Type	Valid range	Description
AngleOfArrivalAzimuth	Float	$-\pi$ to $+\pi$	Angle of arrival of signal in azimuth measured in radians. This parameter is valid only when AngleOfArrivalSupported is set to either AZIMUTH, or BOTH. The real world direction indicated (e.g., by 0 radians) is a system set-up parameter beyond the scope of this standard.
AngleOfArrivalElevation	Float	$-\pi$ to $+\pi$	Angle of arrival of signal in elevation measured in radians. This parameter is valid only when AngleOfArrivalSupported is set to either ELEVATION, or BOTH.
AngleOfArrivalSupported	Enumeration	NONE, BOTH, AZIMUTH, ELEVATION	Indicates validity of AngleOfArrivalAzimuth and AngleOfArrivalElevation. Where the underlying PHY does not support angle of arrival measurement, then this parameter shall be set to NONE.

Table 48—MCPS-DATA.indication parameters *(continued)*

Name	Type	Valid range	Description
RSSI	Integer	0x00–0xff	The Received Signal Strength Indicator is a measure of the RF power level at the input of the transceiver. The RSSI value is based on the gain setting in the RX chain and the measured signal level in the channel. RSSI value is measured during the frame Preamble and locked when valid SFD is detected. (See NOTE)
NOTE—This complements the existing mpduLinkQuality parameter, which may report link quality indications other than signal level.			

8. General PHY requirements

8.1 General requirements and definitions

8.1.1 Operating frequency range

Insert the following rows at the end of Table 66:

Table 66—Frequency bands and data rates

PHY (MHz)	Frequency band (MHz)	Chip rate (kchip/s)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbol/s)	Symbols
433 (optional)	433.05–434.79	N/A	MSK	31.25	31.25	Binary
433 (optional)	433.05–434.79	N/A	MSK	100	100	Binary
433 (optional)	433.05–434.79	N/A	MSK	250	250	Binary
2450 (optional)	2400–2483	N/A	MSK	250	250	Binary
LRP UWB (optional)	6289.6–9185.6	2000	Manchester PPM	31.25	31.25	Binary
LRP UWB (optional)	6289–9185.6	1000	OOK	250	250	Binary
LRP UWB (optional)	6289.6–9185.6	1000	OOK	1000	1000	Binary

8.1.2 Channel assignments

Insert the following new sentence at the end of the last paragraph as shown:

For each PHY supported, a compliant device shall support all channels allowed by regulations for the region in which the device operates. An exception to this is the UWB PHY where specific mandatory and optional behaviors are as defined in 14.4.1. An additional exception to this is the LRP UWB PHY, in which a transmitter device shall not be required to transmit on more than one channel.

Insert the following new subclauses (8.1.2.6, 8.1.2.7, 8.1.2.8) after 8.1.2.5:

8.1.2.6 Channel numbering for MSK PHY 433 MHz band

The MSK PHY 433 MHz band uses channel page 7 with the channel numbers defined in Table 68a. A total of 15 frequency channels are available in the band from 433.05 MHz to 434.79 MHz. Different subsets of these frequency channels are available in different regions of the world. Compliant receivers shall implement all 15 channels in Table 68a, defaulting to channel 7 unless modified by higher layers.

The multiple narrowband channels for the MSK PHY 433 MHz band are specified in order to improve coexistence with other potential 433 MHz services and to comply with local regulations. The selection of specific channels is out of the scope of this standard, being performed by higher layers. Channel selection methodologies might include the following:

- Selecting permanent channels based on an RF survey at the time of system installation
- Performing regular CCAs during operation to dynamically select optimal channels
- Monitoring other link quality metrics to select optimal channels

Table 68a—MSK PHY 433 MHz band channel frequencies

Channel number	Center frequency (MHz)
0	433.164
1	433.272
2	433.380
3	433.488
4	433.596
5	433.704
6	433.812
7	433.920
8	434.028
9	434.136
10	434.244
11	434.352
12	434.460
13	434.568
14	434.676

8.1.2.7 Channel numbering for MSK PHY 2450 MHz band

The MSK PHY 2450 MHz band uses channel page 7 with the channel numbers defined in Table 68b. A total of 42 frequency channels numbered 15 to 56 on channel page 7 are available in the band from 2400 MHz to 2483.5 MHz. Different subsets of these frequency channels are available in different regions of the world. Compliant receivers shall implement all channels in Table 68b, defaulting to channel 47 unless modified by higher layers. The multiple narrow channels for the narrowband MSK 2450 MHZ PHY are specified in order to improve coexistence with other 2450 MHz services. The selection of specific channels is out of the scope of this standard, being performed by higher layers.

Table 68b—MSK 2450 MHz mandatory PHY channel frequencies

Channel number	Center frequency (MHz)
15	2401.75
16	2403.75
17	2405.75
18	2407.75
19	2409.75
20	2411.75
21	2413.75
22	2415.75
23	2417.75
24	2419.75
25	2421.75
26	2422.5
27	2423.25
28	2425.75
29	2427.75
30	2429.75
31	2431.75
32	2433.75
33	2435.75
34	2437.75
35	2439.75
36	2442
37	2443.75
38	2445.75
39	2447.75
40	2449.75

Table 68b—MSK 2450 MHz mandatory PHY channel frequencies *(continued)*

Channel number	Center frequency (MHz)
41	2451.75
42	2453.75
43	2455.75
44	2457.75
45	2459.75
46	2462
47	2463.75
48	2465.75
49	2467.75
50	2469.75
51	2471.75
52	2473.75
53	2475.75
54	2477.75
55	2479.75
56	2481.75

8.1.2.8 Channel numbering for LRP UWB PHY

The LRP UWB PHY uses channel page 8 with the channel numbers defined in Table 68c. A total of three frequency channels, numbered 0 to 2, are available in the 6289.6 MHz to 9185.6 MHz frequency bands. Different subsets of these frequency channels are available in different regions of the world. In North America and Europe, a shared channel may be used.

Table 68c—LRP UWB PHY channel frequencies

Channel number	Center frequency (MHz)
0	6489.6
1	6988.8
2	7987.2

9. PHY services

9.2 PHY constants

Insert the following row at the end of Table 70:

Table 70—PHY constants

Constant	Description	Value
aLeipDelayTime	The delay between the start of the SFD and the LEIP. See 17.5.	0.815 ms

9.3 PHY PIB attributes

Change the following two rows and add a new row at the end of Table 71 as shown:

Table 71—PHY PIB attributes

Attribute	Type	Range	Description
phyTXRMARKER Offset	Integer	0x00000000–0xffffffff	~~A count of the propagation time from the ranging counter to the transmit antenna. The LSB of a time value represents 1/128 of a chip time at the mandatory chipping rate of 499.2 MHz.~~ A count of the propagation time from the ranging counter to the transmit antenna. For the UWB PHY the LSB of a time value represents 2^{-7} of a chip time at the mandatory chipping rate of 499.2 MHz. For the LRP UWB PHY the LSB of a time value represents 2^{-20} of the base mode chipping rate of 1 MHz.
phyRXRMARKER Offset	Integer	0x00000000–0xffffffff	~~A count of the propagation time from the receive antenna to the ranging counter. The LSB of a time value represents 1/128 of a chip time at the mandatory chipping rate of 499.2 MHz.~~ A count of the propagation time from the receive antenna to the ranging counter. For the UWB PHY the LSB of a time value represents 2^{-7} of a chip time at the mandatory chipping rate of 499.2 MHz. For the LRP UWB PHY the LSB of a time value represents 2^{-20} of the base mode chipping rate of 1 MHz.

Table 71—PHY PIB attributes *(continued)*

Attribute	Type	Range	Description
phyReceiveDataRate-Mode	Integer	0–4	This attribute allows selection of receive data rate mode for PHY channels that support more than one data rate. A value of zero means that the PHY data rate is determined automatically or otherwise implied by the *phyCurrentChannel*. A non-zero value specifies the data rate to use in the receiver. The values here are aligned with the MCPS-DATA primitive definition for DataRate in Table 46. A non-zero value is only meaningful where the data rate is not implicitly implied by the *phyCurrentChannel*. When *phyReceiveDataRateMode* is non-zero, the PHY shall deliver frames received at selected data rate and shall ignore and discard any frames arriving at other data rates.

Insert the following new clauses (Clause 16 and Clause 17) after Clause 15:

16. MSK PHY

16.1 PPDU formats

The MSK PHY shall use the PPDU formats described in 10.1, except that the preamble is 32 symbols (4 octets) and the bits in each octet shall be "10101010."

16.2 Data rate

The default data rate of the MSK PHY shall be 250 kb/s. Additional optional data rates for the 433 MHz frequency band are shown in Table 116.

Table 116—Data rates for MSK PHY

DataRate as used in MCPS-DATA primitives	Data rate (kb/s)
1	31.25
2	100
3	250

The optional data rates for the 433 MHz band are not available on all channels. Table 117 shows all permissible data rates for the 433 MHz channels and their associated channel numbers.

Table 117—Data rate channel map

Data rate (kb/s)	Channel
31.25	0 to 14
100	1, 4, 7, 10, 13
250	2, 7, 12

16.3 SFD for MSK PHY

The SFD for the MSK PHY shall be formatted as illustrated in Table 118.

The SFD is transmitted starting from the leftmost bit (b0).

Table 118—Format of the SFD field for MSK PHY

	SFD (b0–b15)
SFD value	1110 0110 1101 0000

16.4 MSK modulation

The MSK PHYs employ CPFSK minimum shift keying, a form of continuous phase frequency shift keying.

16.4.1 Reference modulator diagram

The functional block diagram in Figure 103 is provided as a reference for specifying the MSK PHY modulation. The number in each block refers to the subclause that describes that function. Each bit in the PPDU shall be processed through modulation functions in octet-wise order, beginning with the Preamble field and ending with the last octet of the PSDU. It should be noted the preamble is not included in the whitening scheme. Within each octet, the LSB, b_0, is processed first and the MSB, b_7, is processed last.

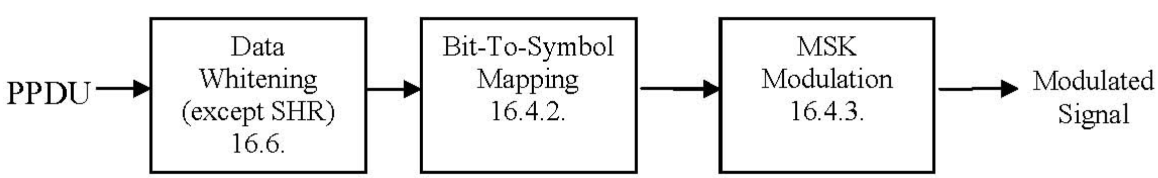

Figure 103—MSK functional block diagram

16.4.2 Bit-to-symbol mapping

Bit rate and symbol rate are equal.

The mapping of bits to frequency shall be as described in Table 119, with

$$\Delta f = \frac{1}{4 \times Tb}$$

NOTE—*f* is *channel center frequency* as defined in Table 68a and Table 68b.

Table 119—Bit to frequency mapping

Bit	Frequency
0	$f - \Delta f$
1	$f + \Delta f$

16.4.3 Signal modulation

The MSK modulation shall be CPFSK with modulation index h = 0.5. This modulation index corresponds to minimum frequency spacing that allows two FSK signals to be coherently orthogonal.

As shown in Figure 104, MSK modulation has two possible frequencies over any symbol interval, which differs in frequency by half the bit rate as follows:

$$f_2 - f_1 = ½\, Tb$$

This is the smallest frequency difference that allows two signals to be orthogonal.

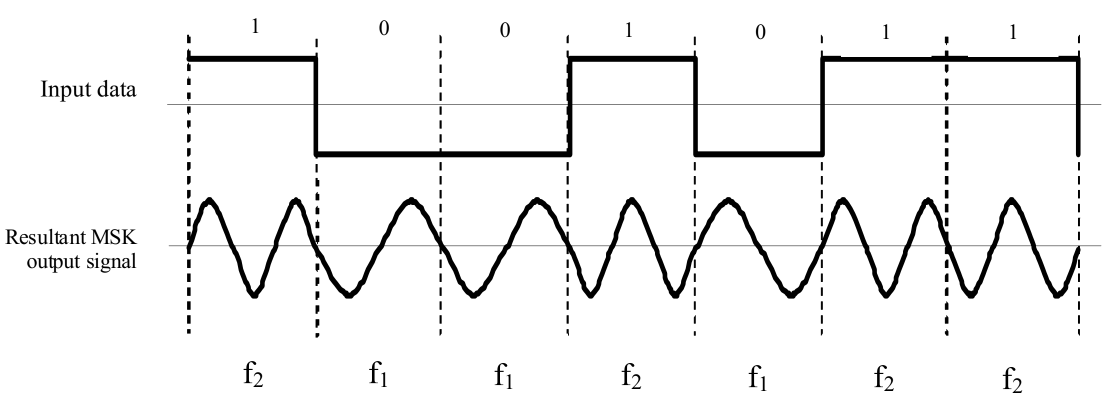

Figure 104—Example signal using MSK modulation in the time domain

16.5 MSK PHY requirements

16.5.1 Operating frequency range

The MSK PHY specifies the following two optional frequency bands:

— 433.05 MHz to 434.79 MHz
— 2400 MHz to 2483 MHz

16.5.2 Transmit PSD mask

The PSD mask for the MSK PHY is shown in Table 120.

The transmitted spectral products shall be less than the limits specified in Table 120. For both relative and absolute limits, average spectral power shall be measured using a 100 kHz resolution bandwidth. For the relative limit, the reference level shall be the highest average spectral power measured within ±600 kHz, ±300 kHz, or ±100 kHz of the carrier frequency (respective to data rate).

Table 120—MSK PHY transmit PSD limit

Frequency band	Data rate	Frequency	Relative limit	Absolute limit
433 MHz	31.25 ksymbols/s	$\|f - fc\| > 200$ kHz	–20 dB	–20 dBm
	100 ksymbols/s	$\|f - fc\| > 600$ kHz	–20 dB	–20 dBm
	250 ksymbols/s	$\|f - fc\| > 1.2$ MHz	–20 dB	–20 dBm
2450 MHz	250 ksymbols/s	$\|f - fc\| > 1.2$ MHz	–20 dB	–20 dBm

16.5.3 Symbol rate

Transmission of the symbol rate for 433 MHz frequency band shall be either 31.25 ksymbol/s, 100 ksymbol/s, or 250 ksymbol/s with an accuracy of ±300 ppm.

The transmitted symbol rate for 2450 frequency band shall be 250 ksymbol/s with an accuracy of ±300 ppm.

16.5.4 Transmit center frequency tolerance

The MSK PHY shall have a transmit center frequency tolerance of ±40 ppm.

16.5.5 Transmit power

The 433 MHz MSK PHY shall be capable of transmitting at a power level of at least –3 dBm.

The 2450 MHz MSK PHY shall be capable of transmitting at a power level of at least –13 dBm.

16.5.6 Receiver maximum input level of desired signal

The MSK PHY shall have a receiver maximum input level greater than or equal to –20 dBm using the measurement as described in 8.1.7.

16.5.7 Modulation frequency deviation tolerance

Modulation frequency tolerance is measured as a percentage of maximum frequency deviation Δf.

Modulation frequency deviation shall be constrained within ±30% of maximum frequency deviation Δf as defined in 16.4.2.

16.5.8 Zero crossing tolerance

All zero crossing shall be constrained within ±12.5% of symbol time (±1/8th of the symbol).

16.6 Data whitening

Data whitening shall be the exclusive OR of the PPDU data (without SHR) with the PN9 sequence. This shall be performed by the transmitter and is given by the following:

$$E_n = R_n \oplus PN9_n$$

where

E_n is the whitened bit
R_n is the data bit being whitened
$PN9_n$ is the PN9 sequence bit

Index n starts after the SFD from 0 and is increased by one every symbol. For each packet transmitted, *R0* is the PHR first raw data bit after the SFD. Conversely, the decoding process, as performed at the receiver, can be described by the following:

$$R_n = RE_n \oplus PN9_n$$

where

RE_n is the PSDU bit at the output of the MSK demodulator
R_n is the PSDU bit after de-whitening

For each packet received, *R0* is the PHR first raw data bit.

The PN generator is defined by the schematic in Figure 105.

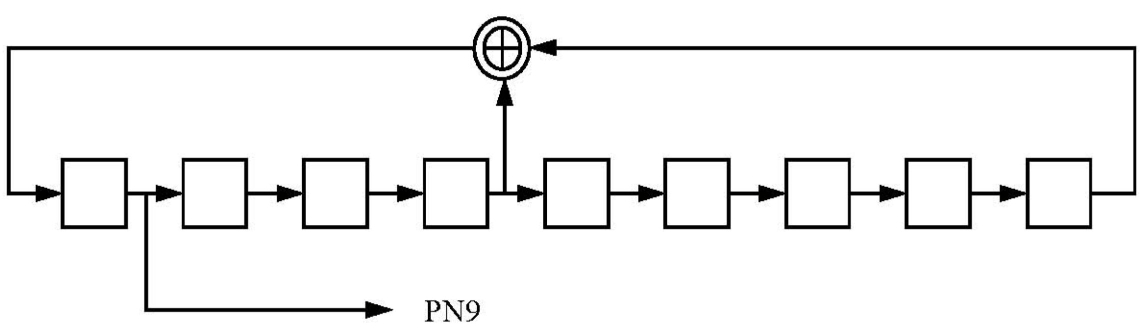

Figure 105—Schematic of PN generator

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

The preamble and the SFD are not whitened. The PN9 generator is clocked starting from the seed. For example, the first 30 bits out of the PN9, once it is enabled, would be as follows:

$PN9_n = 0_0, 0_1, 0_2, 0_3, 1_4, 1_5, 1_6, 1_7, 0_8, 1_9, 1_{10}, 1_{11}, 0_{12}, 0_{13}, 0_{14}, 0_{15}, 1_{16}, 0_{17}, 1_{18}, 1_{19}, 0_{20}, 0_{21}, 1_{22}, 1_{23}, 0_{24}, 1_{25}, 1_{26}, 0_{27}, 1_{28}, 1_{29}$

17. LRP UWB PHY specification

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

The LRP UWB PHY supports the following three transmission modes:

— Base mode, for highest data rate
— Extended mode, for moderate data rate but improved sensitivity
— Long-range mode, for best sensitivity

All transmit modes are optional, but all modes shall be implemented in the receiver and operational concurrently. Active RFID systems are often simplex systems so mandatory modes are not defined for the PHY but separately for the transmitter (RFD-TX) and receiver (RFD-RX).

The PHY has different characteristics depending on the transmission mode. These characteristics are defined for each mode separately as shown in Table 121. Otherwise, the characteristics of the PHY are independent of transmission mode.

Table 121—Signaling modes and data rates (for LRP UWB PHY)

Mode	PRF (MHz)	DataRate as used in MCPS-DATA primitives	Data rate	Modulation
Long-range mode	2.0	1	31.25 kb/s	PPM
Extended mode	1.0	2	250 kb/s	OOK
Base mode	1.0	3	1 Mb/s	OOK

17.1 LRP UWB PHY symbol structure

In base mode, the LRP UWB PHY symbol consists of presence/absence of pulses in 1 MHz PRF train.

In extended mode, the LRP UWB PHY symbol consists of presence/absence of pulses in 1 MHz PRF train generated by convolution code with octal generators (5,7,7,7).

In long-range mode, the LRP UWB PHY symbol consists of Manchester-encoded groups of 64 pulses (32 on, 32 off) in 2 MHz PRF train

17.1.1 Base mode LRP UWB PHY symbol structure

In the base mode of LRP UWB modulation scheme, each symbol carries one bit of information. The base mode operates at 1 chip per symbol and with a PRF of 1 MHz, so the symbol time T_{DSYM} is 1 µs and the chip time T_{CHIP} is also 1 µs. Binary data values 0 and 1 are encoded as per Table 122. The data rate is thus 1 Mb/s. The pulse duration T_{PULSE} is much shorter than the symbol time. The pulse is nominally sent in the center of the chip and symbol period T_{DSYM} as shown in Figure 106.

Table 122—Base mode LRP UWB symbol encoding

Binary value being encoded	Transmitted signal
0	No energy is transmitted during the 1 µs symbol time
1	A single pulse is transmitted during the 1 µs symbol time

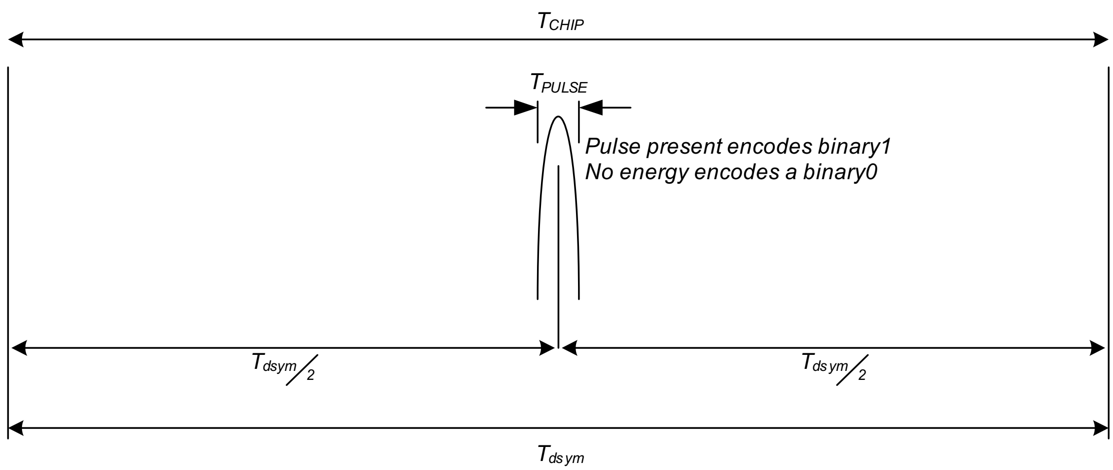

Figure 106—Base mode LRP UWB PHY symbol structure

17.1.1.1 Base mode LRP UWB PHY PSDU synchronization signal

During the base mode PSDU transmission, after every 128 symbols of user data, the PHY inserts four chips of binary 1. This ensures that the receiver has enough information to retain synchronization when the user data is all zeros. These four chips/symbols are removed in the PHY and not decoded as user data.

17.1.2 Extended mode LRP UWB PHY symbol structure

In the extended mode of LRP UWB modulation scheme, each symbol consists of four chips generated by a rate ¼ convolutional code using octal generators 5,7,7,7 for $k = 3$, as shown in Figure 107.

The extended mode receiver may employ a relatively simple Viterbi decoder with hard or soft decisions to make use of the coding gain afforded by the transmitter convolution code.

Extended mode employs a PRF of 1 MHz with a rate ¼ code giving a symbol time of 4 µs. The data rate is thus 250 kb/s. The pulses are nominally centered within the chip periods as shown in Figure 108. These four pulses are transmitted in order with pulse 1 transmitted first. The individual pulses shown here may or may not be present depending on whether the pulse out value is binary 1 or binary 0 as per Table 123.

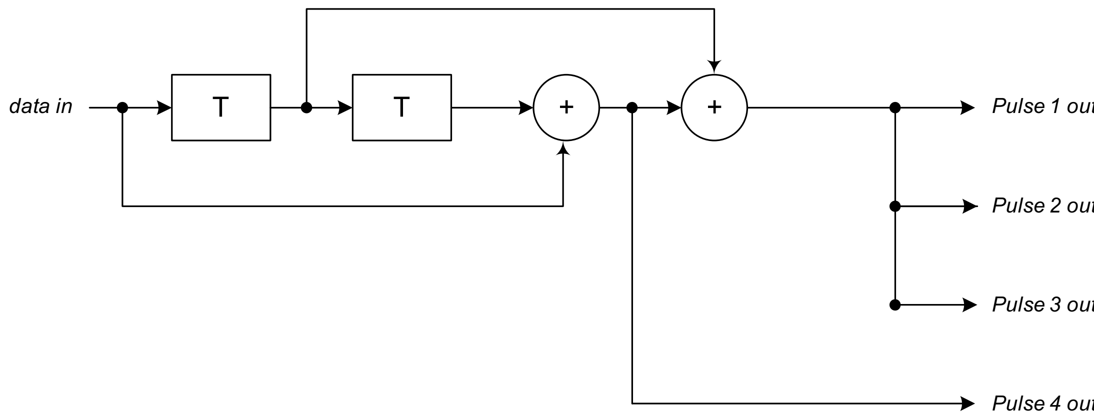

Figure 107—Extended mode LRP UWB PHY transmitter convolution code

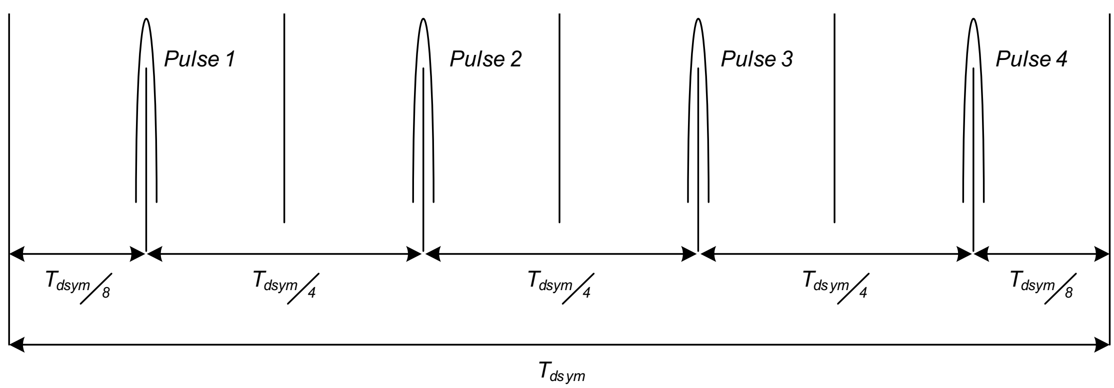

Figure 108—Extended mode LRP UWB PHY symbol structure

Table 123—Extended mode LRP UWB pulse to chip encoding

Pulse out value	Transmitted chip
0	No energy is transmitted during this chip time
1	A pulse is transmitted during this chip time

17.1.2.1 Extended mode LRP UWB PHY PSDU synchronization signal

During the extended mode PSDU transmission, after every 32 symbols of user data, which is (128 chips), the PHY inserts four chips of “1” pulse. This ensures that the receiver has enough information to retain synchronization when the encoded output pulses are "0" pulses (i.e., no transmitted energy). These four chips (1 symbol of pulses) are removed in the PHY before the received pulse (Viterbi) decoding.

17.1.3 Long-range mode LRP UWB PHY symbol structure

In the long-range mode of the LRP UWB modulation scheme, each symbol encodes one bit using 64 chips at a chipping rate of 2 MHz PRF, with Manchester encoding as given in per Table 124. The data rate is thus 31.25 kb/s. Figure 109 shows this diagrammatically. When a pulse is present, it is nominally centered within the chip period.

Table 124—Long-range mode LRP UWB symbol encoding

Binary value being encoded	Transmitted signal
0	The symbol period is 32 µs (64 chip times). No energy is transmitted during first 16 µs (32 chip times), and then in the second 16 µs (32 chip times) 32 pulses are transmitted.
1	The symbol period is 32 µs (64 chip times). In the first 16 µs (32 chip times) 32 pulses are transmitted, and then no energy is transmitted during second 16 µs (32 chip times).

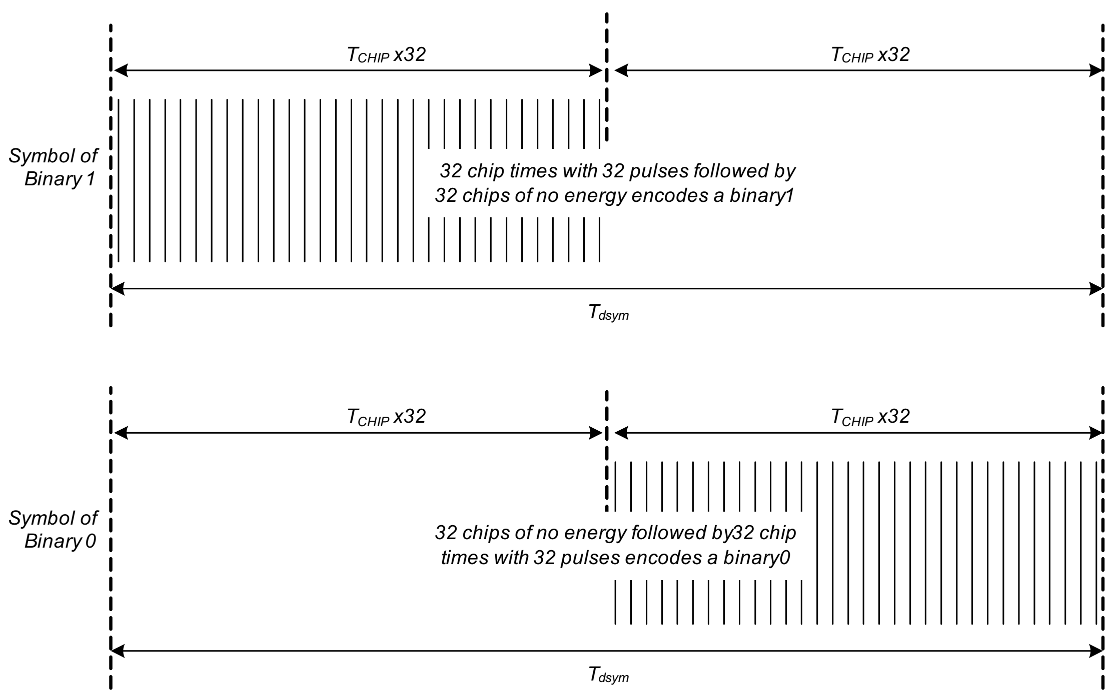

Figure 109—Long-range mode LRP UWB PHY symbol structure

17.1.3.1 Long-range mode LRP UWB PHY PSDU synchronization signal

No additional synchronization measures are needed in long-range mode since its Manchester encoding scheme ensures that sufficient pulses are transmitted.

17.2 LRP UWB SHR

The SHR consists of two components: the preamble and SFD. The following subclauses describe the formats of the preamble and SFD for the different LRP UWB PHY transmission modes.

17.2.1 LRP UWB SHR preamble

17.2.1.1 LRP UWB base mode SHR preamble

The LRP UWB base mode SHR preamble consists of a continuous stream of pulses at the base mode PRF of 1 MHz, with a length between 16 and 128.

17.2.1.2 RP UWB extended mode SHR preamble

The LRP UWB extended mode SHR preamble consists of a continuous stream of pulses at the extended mode PRF of 1 MHz, with a length between 16 and 256.

17.2.1.3 LRP UWB long-range mode SHR preamble

The LRP UWB long-range mode SHR preamble consists of three segments, which are transmitted in turn, as follows:

a) A continuous stream of pulses at the long-range mode PRF of 2 MHz, with a length between 1024 and 8192 pulses.
b) The following pulse/no-pulse sequence, transmitted at a PRF of 2 MHz where "-" represents "no pulse," and "P" represents a pulse:
   - - - P - P - - P - - P P P - P
c) A series of between 16 and 64 "1" symbols, transmitted as per the long-range mode PHY symbol structure defined in 17.1.3.

17.2.2 LRP UWB SHR SFD

The SFD for the LRP UWB PHY is common to all modes and shall be formatted as illustrated in Table 125. The modulation encoding for the SFD shall be 1 pulse per bit for both the base and extended modes. The modulation encoding for the long-range mode shall be Manchester encoded with 64 chips per bit as specified for long-range mode.

The SFD is transmitted starting from the leftmost bit (b0).

Table 125—Format of the SFD field for LRP UWB PHY

	SFD (b0–b15)
SFD value	0001 0100 1001 1101

17.3 LRP UWB PHY Header (PHR)

This is defined in symbols and is therefore common to base, extended, and long-range modes, with the exception of the encoding type (bits 0–2). The encoding type is defined in symbols for long-range mode and as pulses for basic and extended mode.

The PHY Header field of the LRP UWB modulation as shown in Figure 110 is inserted between the SFD and the PSDU. The PHR contains information about the modulation mode used to transmit the PSDU, the length of the frame payload, and the specification for the optional *location enhancing information postamble* (LEIP) sequence. Additionally, six parity check bits are used to further protect the PHR against channel errors. The sub-fields of the PHR header are defined in individual subclauses that follow.

Bit 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
E2	E1	E0	EXT	C5	C4	C3	C2	C1	C0	L6	L5	L4	L3	L2	L1	L0	R	LL2	LL1	LL0	LP
Encoding Type			Header Extension	SECDED Check Bits						Frame Length							Reserved	LEIP Length			LEIP Position

Figure 110—PHR bit assignment in LRP UWB PHY

17.3.1 PHR Encoding Type field

Long-range mode is specified (and detected) by its own unique symbol mapping, defined in 17.1.3, and the use of a 2 MHz PRF. In long-range mode the Encoding Type field of the PHR is given by Table 126.

Table 126—PHR Encoding Type field in long-range mode

Encoding Type value E2–E0	Meaning
000	Each symbol encodes 1 bit. Each symbol consists of 64 chips and uses Manchester encoding. This encoding is defined in 17.1.3
001 to 111	Reserved

In base mode and extended mode where the PHR is sent with a chip rate of 1 MHz, the Encoding Type field of the PHR is given by Table 127. These three bits are encoded as per 17.1.1. Only two values are legal, 000 and 111. This allows a receiver to use all three bits in a voting scheme to determine whether it should switch to using extended mode decoding for the remainder of the PHR and the PSDU or should continue decoding the PHR and PSDU in base mode.

Table 127—PHR Encoding Type field base mode and extended mode

Encoding Type value E2–E0	Meaning
000	This value indicates the operating mode is base mode. All remaining bits in the frame continue to be encoded as per 17.1.1.
111	This value indicates the operating mode is extended mode. All bits in the remaining fields of the PHR and PSDU are encoded as per 17.1.2.
001 to 110	ILLEGAL—These values can never be legally used. The receiver may use all three bits of the two legal values 000 and 111 in a voting scheme to decide which is actually present.

17.3.2 PHR Header Extension bit

The PHR Header Extension bit shall be set to zero upon transmission. If a PPDU is received with the PHR Header Extension bit set, the device shall discard the PPDU.

17.3.3 PHR SECDED check bits

The SECDED (single error correct, double error detect) field, C5–C0, is a set of six parity check bits that are used to protect the PHR from errors caused by noise and channel impairments. The SECDED bits are a simple Hamming block code that enables the correction of a single error and the detection of two errors at the receiver. The SECDED bit values depend on PHR bits 0–21 and are computed as follows:

C0 = *XOR* (LP, LL2, LL1, LL0, R)

C1 = *XOR* (L6, L5, L4, L3, L2, L1, L0)

C2 = *XOR* (E1, E0, EXT, L3, L2, L1, L0, LL0, R)

C3 = *XOR* (E2, E0, EXT, L5, L4, L1, L0, LL2, LL1)

C4 = *XOR* (E2, E1, EXT, L6, L4, L2, L0, LP, LL1, R)

C5 = *XOR* (all bits including C0 to C4, but excluding C5)

17.3.4 PHR Frame Length field

The Frame Length field shall be set to the length of the PSDU in octets in which L0 represents the LSB (e.g., b0000001 {L6–L0} ≡ Frame Length 1).

17.3.5 Reserved bit

This bit is reserved for future use. It shall be set to zero upon transmission and may be ignored upon receipt.

17.3.6 PHR LEIP Length field

This gives the length of the LEIP in pulses. The meaning of this field is defined in Table 128.

Table 128—PHR LEIP Length field meaning

LEIP Length field value LL2–LL0	Meaning
000	The LEIP sequence is not present.
001	The LEIP sequence is 16 pulses in length
010	The LEIP sequence is 64 pulses in length
011	The LEIP sequence is 128 pulses in length
100	The LEIP sequence is 192 pulses in length.
101	The LEIP sequence is 256 pulses in length.
110	The LEIP sequence is 512 pulses in length.
111	The LEIP sequence is 1024 pulses in length.

17.3.7 PHR LEIP position bit

This bit specifies the position of the optional LEIP sequence. This bit only applies if the LEIP Length field has a nonzero value, in which case the meaning of this bit is then as defined in Table 129. When the LEIP Length field is 000, then the LEIP Position Bit is reserved, and thus shall be set to zero upon transmission and may be ignored upon receipt.

17.3.7.1 PHR LEIP delay

When the LEIP sequence is delayed, it is delayed by *aLeipDelayTime* from start of SFD. The LEIP then starts on the first chipping interval after the delay. Where the PSDU is of sufficient length that it has not ended by this time, then the LEIP is deferred to start in the chipping interval immediately following the final chipping interval being used for the PSDU.

When the LEIP is not delayed, the LEIP starts in the chipping interval immediately following the final chipping interval being used for the PSDU.

Table 129—PHR LEIP position bit meaning

LEIP position bit value LP	Meaning
0	The LEIP is delayed; see 17.3.7.1.
1	The LEIP is not delayed; see 17.3.7.1.

17.4 LRP UWB PSDU

In base mode the PSDU is encoded as per 17.1.1; in extended mode the PSDU is encoded as per 17.1.2; and in long-range mode the PSDU is encoded as per 17.1.3.

17.5 LRP UWB location enhancing information postamble

The LEIP consists of a train of UWB pulses. The PRF of the LEIP pulse train is as follows:

— 1 MHz in the LRP UWB base and extended modes, and

— 2 MHz in the long-range mode.

Information in the PHY header (see 17.3) indicates whether or not the LEIP is appended to a transmitted packet.

If the information in the PHY header indicates that the LEIP is appended to the transmitted packet, further information in the PHY header indicates when the first LEIP pulse occurs immediately. It occurs either:

— Immediately after the end of the PSDU, or

— *LeipDelayTime* after the start of the SHR SFD.

The length of the LEIP (in pulses, at the appropriate rate) is defined in Table 128 by the PHR LEIP length field.

17.6 LRP UWB transmitter specification

17.6.1 Pulse shape

The LRP UWB_UWB PHY shall employ an impulse transmitter that instantaneously produces an ultra wideband frequency response. There are no constraints on the specific pulse shape providing that the pulse shall comply with the Transmit PSD Mask defined in 17.6.3.

17.6.2 Pulse timing

The transmission time of any individual pulse shall not drift more than 11 ns from its nominal transmission time during a 128 symbol period over the specified operating temperature range of the device.

In order to avoid long sequences of zeros driving the need for high-quality clocks, the symbol structure in the base and extended modes includes a periodic sync marker as described in 17.1.1.1 and 17.1.2.1. No additional sync marker is required in the long-range mode.

17.6.3 Transmit PSD mask

The transmitter shall operate with a power spectral density contained by one of three PSD masks defined in Table 130 and shown in Figure 111. The permitted spectral density is defined in dBr relative to the maximum spectral density of the signal, and shall be made using a 1 MHz resolution bandwidth and a 1 MHz video bandwidth. Additionally, the upper −10 dBr point of the transmitter PSD shall be at least 200 MHz above a nominal frequency, f_n, and the lower −10 dBr point shall be at most 200 MHz below the same nominal frequency.

Table 130—LRP UWB PHY PSD mask

Band number	f_n (MHz)	Frequency (MHz)	PSD limit (dBr)
0	6489.6	< 5624.32	−18
		5624.32 to 5786.56	−10
		5786.56 to 7192.64	0
		7192.64 to 7354.88	−10
		> 7354.88	−18
1	6988.8	< 6090.24	−18
		6090.24 to 6165.12	−10
		6165.12 to 8311.68	0
		8311.68 to 8386.56	−10
		> 8386.56	−18
2	7987.2	< 6922.24	−18
		6922.24 to 7121.92	−10
		7121.92 to 8852.48	0
		8852.48 to 9052.16	−10
		> 9052.16	−18

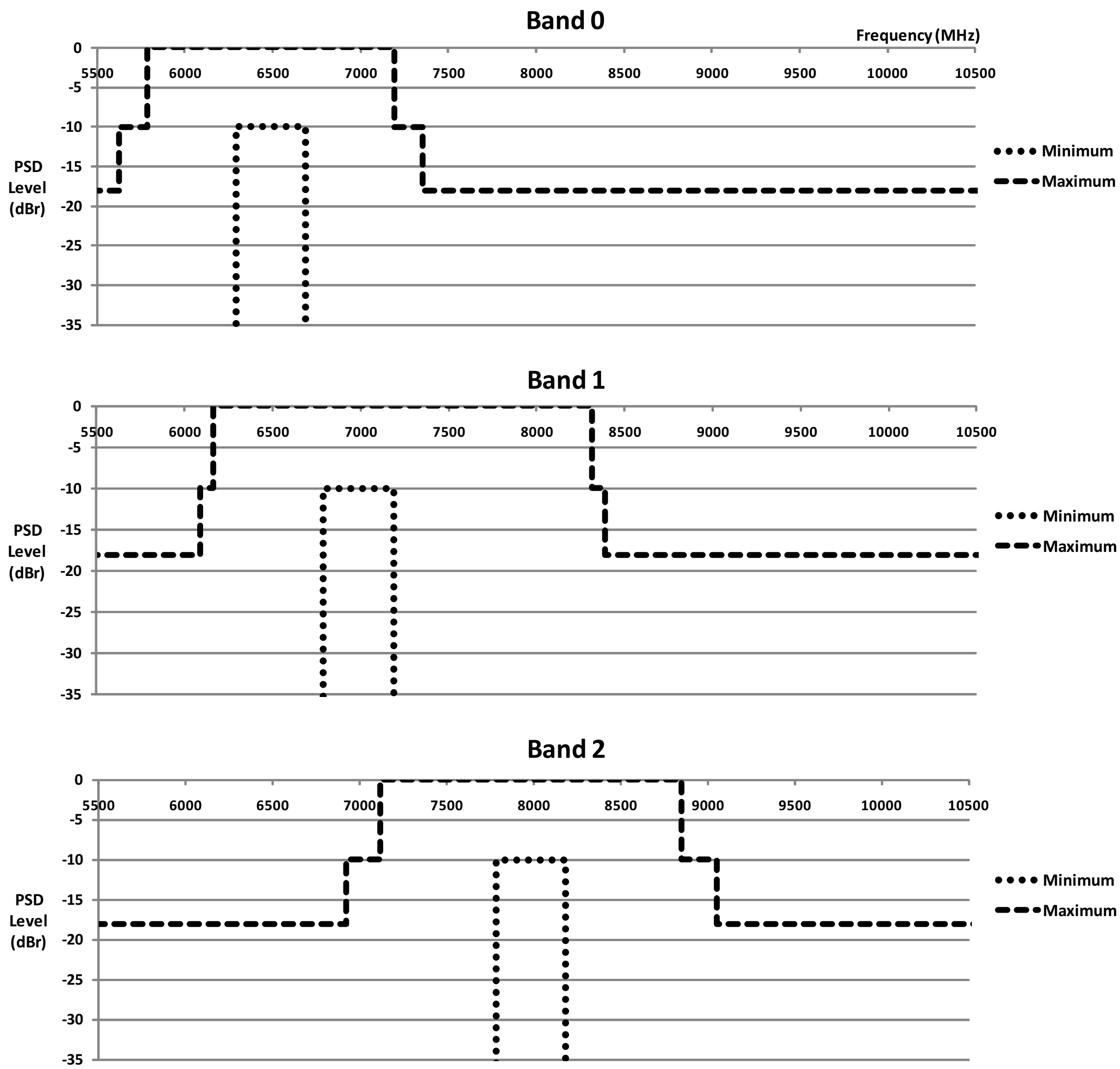

Figure 111—Low rate PRF PHY PSD mask

17.7 LRP UWB receiver specification

The receiver shall support each mode of operation: base mode, extended mode and long-range mode.

Receiving devices shall be capable of receiving at least one channel allowed by regulations for the region(s) in which the device operates.

Annex A

(informative)

Bibliography

Insert the following new entry alphanumerically in Annex A:

[B22] TG4f Coexistence Assurance Document, Doc. IEEE 15-10-0918-01-004f, November 2010.

Annex D

(informative)

Protocol implementation conformance statement (PICS) proforma

D.2 Abbreviations and special symbols

Insert the following at the end of "Notations for requirement status":

(item number || item number) Applies to all item numbers listed

Insert the following text as shown:

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.

Example notation (FD1 || FD2 || FD6): M is the same as:
FD1 : M
FD2 : M
FD6 : M

D.7 PICS proforma tables

D.7.1 Functional device types

Change the following row and insert new rows in Table D.1 as shown:

Table D.1—Functional device types

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
FD5	Support of short network address (16 bit)	5.2.1.1.6	~~M~~ (FD1 || FD2): M (FD6 || FD7): O			
FD6	Reduced function-transmit device (RFD-TX)	4.1	O.1			
FD7	Reduced function-receive device (RFD-RX)	4.1	O.1			
O.1 At least one of these features shall be supported.						

D.7.2 Major capabilities for the PHY

D.7.2.1 PHY functions

Change the following rows and insert new rows in Table D.2 as shown:

Table D.2—PHY functions

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
PLF2	Link quality indication (LQI)	8.2.6	~~M~~ (FD1 || FD2): M (FD6 || FD7): O			
PLF3	Channel selection	8.1.2	~~M~~ (FD1 || FD2): M (FD6 || FD7): O			
PLF4.4	Mode 4	~~14.4.15~~ 8.2.7	~~RF4: O.6~~ O.2			
PLF7	Base mode	17.2.1	RF11.1: M RF11.2: O:9			
PLF8	Extended mode	17.2.1	RF11.1: M RF11.2: O:9			
PLF9	Long-range mode	17.2.1	RF11.1: M RF11.2: O:9			
0.9 At least one of these features shall be supported.						

D.7.2.2 Radio frequency (RF)

Insert the following new rows at the end of Table D.3:

Table D.3—Radio frequency (RF)

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
RF10	MSK PHY	8.1, Clause 16, Table 68a Table 68b	O.3			
RF11	6289.6–9185.6 LRP UWB PHY	8.1, Clause 17, Table 68c	O.3			
RF11.1	An LRP UWB RFD-RX	8.1, Clause 17, Table 68c	O.3			
RF11.2	An LRP UWB RFD-TX	8.1, Clause 17, Table 68c	O.3			

D.7.2.3 Channel capabilities for UWB PHY

Insert the following new rows at the end of Table D.4:

Table D.4—UWB Channels

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
PCH17	Channel Number 0	Table 68c	RF11: O.10			
PCH18	Channel Number 1	Table 68c	RF11: O.10			
PCH19	Channel Number 2	Table 68c	RF11: O.10			
O.10 At least one of these features shall be supported.						

D.7.3 Major capabilities for the MAC sublayer

D.7.3.1 MAC sublayer functions

Change the following rows in Table D.5 as shown:

Table D.5—MAC sublayer functions

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
MLF1	Transmission of data	6.3	~~M~~ (FD1 || FD2 || FD6): M FD7: O			
MLF1.1	Purge data	6.3.4, 6.3.5	FD1: M ~~FD2: O~~ (FD2 || FD6 || FD7): O			
MLF2	Reception of data	6.3	~~M~~ (FD1 || FD2 || FD7): M FD6: O			
MLF2.1	Promiscuous mode	5.1.6.5	FD1: M ~~FD2: O~~ (FD2 || FD6 || FD7): O			
MLF3	Beacon management	Clause 5	~~M~~ (FD1 || FD2): M (FD6 || FD7): O			

Table D.5—MAC sublayer functions *(continued)*

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
MLF3.1	Transmit beacons	Clause 5, 5.1.2.4	FD1: M ~~FD2: O~~ (FD2 || FD6 || FD7): O			
MLF3.2	Receive beacons	Clause 5, 6.2.4	~~M~~ (FD1 || FD2): M (FD6 || FD7): O			
MLF6	Frame validation	6.3.3, 5.2, 5.1.6.2	~~M~~ (FD1 || FD2 || FD7): M FD6: O			
MLF7	Acknowledged frame delivery	Clause 5, 6.3.3, 5.2.1.1.4, 5.1.6.4	~~M~~ (FD1 || FD2): M (FD6 || FD7): O			
MLF8	Association and disassociation	Clause 5, 6.2.2, 6.2.3, 5.1.3	~~M~~ (FD1 || FD2): M (FD6 || FD7): O			
MLF10.1	ED	5.1.2.1, 5.1.2.1.1	FD1: M ~~FD2: O~~ (FD2 || FD6 || FD7): O			
MLF10.2	Active scanning	5.1.2.1.2	FD1: M ~~FD2: O~~ (FD2 || FD6 || FD7): O			
MLF10.3	Passive scanning	5.1.2.1.2	~~M~~ (FD1 || FD2): M (FD6 || FD7): O			
MLF10.4	Orphan scanning	5.1.2.1, 5.1.2.1.3	~~M~~ (FD1 || FD2): M (FD6 || FD7): O			

Annex E

(informative)

Location topics

E.1 Overview

E.1.6 Accounting for internal propagation paths

E.1.6.1 PIB attributes for internal propagation paths

Change the text as follows:

This standard provides a defined place to go to for the correction factors characterizing the delays of the internal propagation paths. There are two separate PHY PIB attributes that separately cover the transmit and receive paths. ~~The LSB of these values represents a time interval of about one-half of a centimeter of travel at the speed of light and is the same size as used throughout the ranging computations.~~ The intended use of these PIB attributes is for them to be written by the application at a time of the application's choosing and for the values to stay with the device until rewritten. One possible way for the application to learn what values to write to the PIB attributes is to invoke the CALIBRATE primitives. This standard does not mandate that the CALIBRATE primitives must be used. The standard simply makes them available for use, if desired.

Insert the following new Annex J after Annex I:

Annex J

(informative)

Using IEEE 802.15.4 for active RFID applications

J.1 Introduction

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

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

Active RFID systems are generally characterized by the following attributes:

— Very low cost, low energy consumption tags
— Large populations of tags
— Low duty-cycle transmissions
— A variety of readers from very short range (a few meters) to very long range (hundreds of meters)
— Very short packet lengths, often with no data beyond the device ID and a small number of status bits
— Sensor data may also be transmitted

IEEE Std 802.15.4-2011 contains various MAC mechanisms targeted at enabling active RFID applications and three PHYs particularly suitable for this purpose, as follows:

— LRP UWB PHY
— UWB PHY
— MSK PHY

This annex describes how these PHYs and MAC features can be configured for active RFID applications.

J.2 Overview of active RFID PHYs

J.2.1 LRP UWB PHY

J.2.1.1 Description

The *low rate PRF ultra wideband* (LRP UWB) PHY is a low complexity PHY optimized for active RFID devices. In active RFID systems the hardware components are highly asymmetric, with large populations of very low complexity tags being identified by much smaller populations of potentially complex readers. Typically a tag transmits messages to a reader, although the reverse architecture is also possible (though less common).

The LRP UWB PHY has therefore been predominantly driven by the need for very low complexity transmitters (tags). Low complexity considerations include the following:

- Simple to implement modulation
- No data encoding or whitening in base mode
- Simple to implement PSD mask
- No dithering of pulses for spectral smoothing
- Relaxed timing requirements

Additionally, the low rate PRF is a key feature that reduces location ambiguity and improves the performance of non-coherent receivers in high RF multipath environments.

The low complexity approach drives low energy consumption and low cost in discrete device implementations, which are common in lower volume applications. Where very high volumes of devices are sold, silicon solutions are viable and the UWB PHY becomes a feasible active RFID solution (see J.2.2).

The following subclauses highlight the key features of each mode of operation.

J.2.1.1.1 Base mode

The base mode is the lowest complexity mode. It is used where there is a requirement for very large tag populations, but no requirement for very long-range operation. Typically long range is not an issue in environments with a large number of line-of-sight obstructions.

The key base mode attributes are as follows:

- Very simple modulation (OOK)
- No further encoding or whitening
- Shortest packet length
- Packet length designed to achieve maximum pulse amplitude under global UWB regulations (192 pulses at 1 MHz PRF)

This last point makes the base mode particularly useful for non-coherent (RF energy detect) receivers that benefit from instantaneous pulse amplitude.

A receiver encountering an incoming stream of UWB pulses will go through a process similar to the following in ascertaining whether it is receiving a base mode packet:

- A tone check on the incoming preamble to identify a 1 MHz pulse train (i.e., not a long-range mode packet)
- An SFD search, with a match confirming one of either base mode or enhanced mode
- A check of the first three bits of the PHR (the three bits immediately following the SFD) to confirm base mode
    - Three zeros = base mode
    - Three ones = extended mode
    - The receiver may choose to vote on the first three bits of the PHY header in a “best of three” manner in order to introduce simple error-proofing on the Encoding Type bits.

It should be noted that the preamble length is variable between 16 pulses and 128 pulses at the discretion of the implementer. Sixteen pulses have been shown to be sufficient for a wide variety of use cases, but the implementer may desire to improve acquisition performance by increasing the preamble length. However, doing so has three important negative effects on overall system performance, so the choice should be carefully considered. A longer preamble will:

— Risk increasing the packet length beyond 192 pulses, which may require the pulse amplitude to be reduced in order to comply with local UWB average emission limits.
— Increase power consumption in the tag (more pulses transmitted and more processor on-time).
— Increase tag packet collisions (due to longer packets).

J.2.1.1.2 Extended mode

The extended mode adds rate 1/4 convolutional code to provide simple forward error correction to the base mode for improved performance in certain circumstances. Additionally, the extended mode allows for a longer preamble (up to 256 pulses) if the implementer needs to increase acquisition robustness. The encoding scheme is simple to implement in the transmitter, and allows for two different decoding schemes in the receiver.

Since the extended mode packet length is longer than a base mode packet, the signal is likely to become constrained by the regulatory average emission limits for UWB. This requires individual pulse amplitudes to be reduced, which causes a loss in terms of link budget when using a non-coherent receiver. This loss is to be weighed against an expected coding gain of up to 4 dB to determine whether extended mode has net benefit in any given circumstance.

In general the use of extended mode is a trade-off, balancing coding gain with packet length (i.e., pulse energy loss). The packet length will be determined by a number of factors including preamble length, addressing mode used, and payload size.

The receiver process for identifying an extended mode packet is the same as for the base mode.

J.2.1.1.3 Long-range mode

The long-range mode is targeted at coherent receivers that can leverage coherent pulse integration in order to increase symbol energy. Since multiple pulses are integrated together to form a single symbol, packet length can be long, meaning the pulse amplitude is certainly defined by regulatory average emission limits for UWB. However, coherent pulse integration more than compensates for the loss in pulse energy for a net gain in link budget.

The performance of a coherent receiver depends primarily on two factors: the accuracy of the template pulse used in the receiver, and the accuracy of the timing synchronization at the pulse level between the receiver and the transmitter. The LRP UWB PHY does not make stringent demands on either of these parameters; this is intentional in order to allow for low cost implementations (without sophisticated timing or pulse shaping). For this reason there is a limit to the extent that coherent gain can be achieved by simply adding more pulses per symbol. There is also a pulse amplitude penalty when adding more pulses due to regulatory limits. The parameters selected for the long-range mode therefore represent the peak performance for a coherent receiver with relatively relaxed timing and pulse shaping; longer symbols would add little to coherent gain and only serve to reduce pulse energy.

The long-range mode uses Manchester encoded binary PPM as a modulation scheme, rather than simple OOK as in the base and extended modes, and operates at a 2 MHz PRF. It also uses a more complex preamble necessary to support this encoding scheme. The preamble consists of the following:

— A sequence of between 1024 and 8192 pulses, then
— The SFD encoded as per the base and extended modes, then
— A sequence of between 16 and 64 binary 1 symbols encoded as per the long-range mode

The preamble is then followed by the SFD encoded as per the long-range mode. The purpose of this more complex preamble is to allow a coherent receiver to detect a long-range mode packet and achieve symbol synchronization before the SFD, and also to allow a non-coherent receiver to achieve synchronization (see J.2.1.2).

A receiver encountering an incoming stream of UWB pulses will go through a process similar to the following in ascertaining whether it is receiving a long-range mode packet:

— A tone check on the incoming preamble to identify a 2 MHz pulse train (i.e., not a base or extended mode packet).
— A wait for the start of pulse transitions in the form of 32 present pulses followed by 32 absent pulses, repeating. At this point the receiver will use these transitions to achieve symbol synchronization.
— An SFD search, with a match confirming long-range mode.
— A check of the first three bits of the PHR (the three bits immediately following the SFD) with "000" reconfirming long-range mode (other values are reserved for future use).

J.2.1.2 Mixed mode networks

J.2.1.2.1 Performance considerations

The long-range mode is primarily targeted at coherent receivers, whereas the base and extended modes are primarily targeted at non-coherent receivers. Since active RFID systems are generally part of a fixed infrastructure, it is unlikely that a mix of coherent and non-coherent receivers will be deployed in any given location. Instead, the characteristics of the location will demand one or the other type of receiver for best overall system performance.

For example, an indoor environment with many obstructions, such as a warehouse or manufacturing facility, may not afford a long line of sight distances and so extended range is not useful. Instead, a higher density of non-coherent receivers is likely to be deployed with tags operating either in base mode or extended mode.

By contrast, large open space such as outdoors will afford very much longer line of sight distances, so a lower density of longer range receivers might be more cost-effective. In this case a coherent receiver infrastructure may be deployed with tags operating in long-range mode.

There are many cases, however, where tags may roam from coherent to non-coherent infrastructure, and so this standard requires that all receivers, coherent or non-coherent, are able to receive and demodulate all modes. The "cross" cases do suffer from performance limitations as follows:

A non-coherent receiver will have a short range of operation with a long-range mode tag when compared to either a base or extended mode tag. A long-range mode tag has relatively long packets that cause the emissions to be regulated by UWB average emission limits. This means that long-range mode pulses are smaller in amplitude than base or extended mode pulses. Since a non-coherent receiver relies on single pulse amplitude for reception, it cannot receive the smaller long-range mode pulses over a comparable range. Because of the shorter range of operation, a long-range tag may be only intermittently detected within a network of non-coherent receivers, and location of the tag may not be possible.

A coherent receiver will have a short range of operation with a base or extended mode tag when compared to a long-range mode tag. The base and extended mode tags do not provide sequences of pulses sufficient for coherent pulse integration, which negates the coherent receiver advantage. However, a coherent receiver may operate with similar range to a non-coherent receiver when operating with base and extended mode tags. Since coherent receivers will generally be deployed more sparsely than non-coherent receivers, a base or extended mode tag may be only intermittently detected within a network of coherent receivers and location of the tag may not be possible

The cross-case characteristics are summarized in Table J.1.

Table J.1—Cross-case characteristics

Receiver type	Tag mode	Reception range	Notes
Non-coherent	Base	Good	Typical configuration for large populations of very simple tags
	Extended	Better	Extended range operation in some circumstances
	Long range	Shortened	Short-range reception means tag detection coverage will be intermittent in typical non-coherent networks
Coherent	Base	Good	Wider spacing of coherent receivers means tag detection coverage will be intermittent in typical networks
	Extended	Better	
	Long range	Best	Typical configuration for smaller tag populations in open areas

J.2.1.2.2 Receiver processing considerations

Any of the three modes can be easily decoded by any receiver type once the RF signal has been converted to baseband. The key to operation in the cross cases is to be able to synchronize and demodulate the incoming RF.

When a coherent receiver detects a pulse train at 1 MHz PRF, indicating a base or extended mode packet, it should start to search for the preamble encoded as per the base and extended modes. Once the preamble is detected, and synchronization achieved, the remainder of the packet can be demodulated as per a non-coherent receiver.

When a non-coherent receiver detects a 2 MHz pulse train, then a long-range mode packet is indicated. The receiver may run its normal acquisition/SFD sync process, but at a 2 MHz rate. The insertion of the base/extended mode SFD in the long-range mode preamble facilitates this functionality.

After the inserted SFD, the non-coherent receiver will start to demodulate bits with allowance for the pulse repetition and Manchester encoding. This might be accomplished by running the normal OOK engine at 2 MHz and appending a compression step that translates the 32 pulse repetition Manchester PPM into actual bits. This is depicted in Figure J.1.

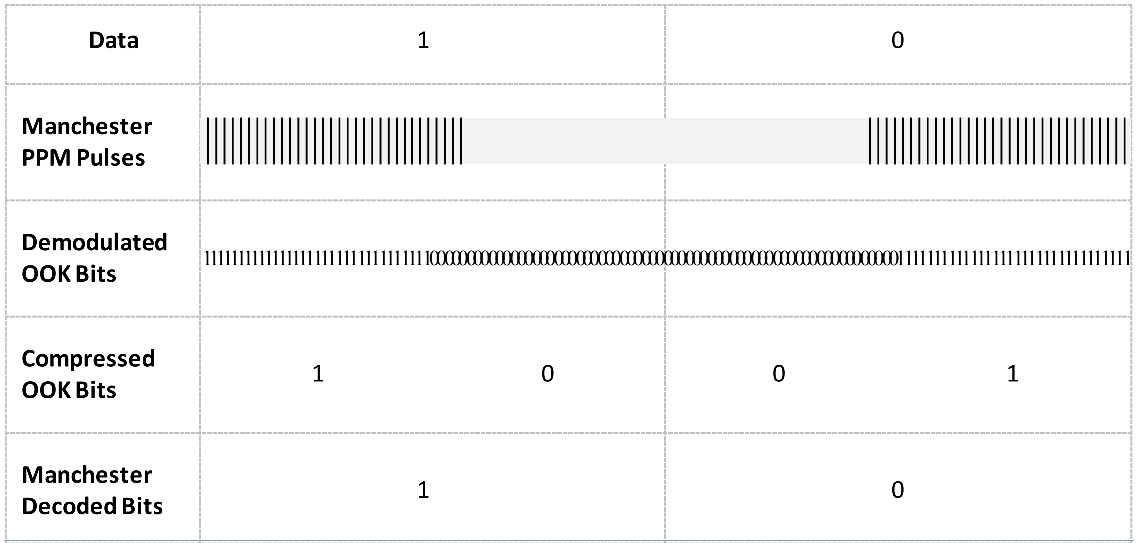

Figure J.1—Converting Manchester PPM to OOK using digital bit compression

Alternatively the non-coherent receiver may take an analog approach, averaging pulses over a 32 pulse window, and then applying OOK demodulation and Manchester decoding as depicted in Figure J.2.

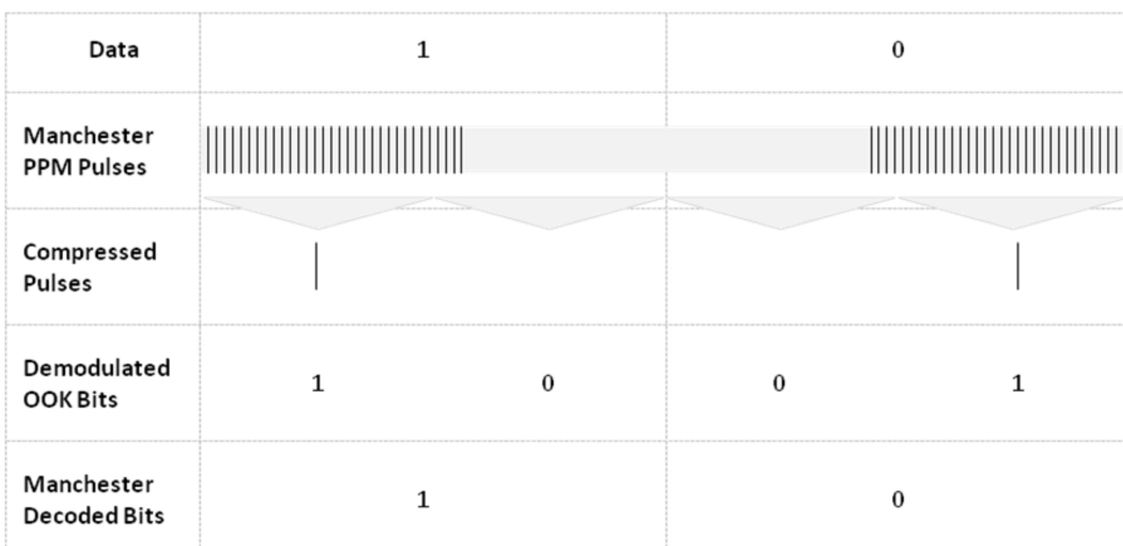

Figure J.2—Converting Manchester PPM to OOK using analog pulse compression

After detecting the SFD, a non-coherent receiver should ignore the sequence of “1” symbols (transmitted to aid coherent receiver synchronization) and search for the “000” normal SFD, encoded as long-range mode symbols, as a trigger to start demodulation of the rest of the packet. It is likely that some implementers will choose to utilize the inserted “1” symbols for positioning purposes if desired.

J.2.1.3 Timing and synchronization

A receiver requires regular pulses in order to maintain bit synchronization. The Manchester encoding in the long-range mode ensures that there are plenty of synchronization pulses, since both data “1” and data “0” contain pulses. However, the base and extended modes use OOK modulation, where a data “0” is denoted by the absence of a pulse. In this case a long string of zeros will cause a long period with no pulses, which in turn causes a synchronization issue.

One method of dealing with long periods with no pulses is for devices to employ very high quality timing systems that enable synchronization to be maintained over long periods with no inputs. However, in keeping with the desire to allow the use of low cost components in active RFID devices, a better approach is to ensure that there are never any long periods without pulses.

The LRP UWB PHY therefore requires that the transmitter insert a sequence of four pulses after every 128^{th} chip (pulse). These pulses ensure a regular synchronization signal and are to be ignored by the receiver PHY.

The standard states that the transmission time of any individual pulse shall not drift more than 11 ns from its nominal transmission time during a 128 symbol period over the specified operating temperature range of the device. The inserted sync pulses ensure that this can be achieved using standard AT-cut crystals over normal temperature ranges. Devices specified for wider temperature ranges may need to use temperature compensated crystals to maintain synchronization. The 11 ns figure ensures that bit boundaries are maintained sufficient to minimize bit errors due to timing offsets.

J.2.2 UWB PHY

The *ultra wideband* (UWB) PHY was introduced into the standard as a high mobility, long-range PHY for industrial environments, with the capability to locate devices with better than 1 m accuracy. Although the modulation and encoding schemes to achieve this goal are complex, device cost can be minimized through silicon-based solutions.

Generally speaking, the LRP UWB PHY is advantageous when the market dynamics favor discrete device implementation; whereas the UWB PHY becomes attractive when device volumes are sufficiently high to justify silicon integration. The high bit rate of the UWB PHY allows its packet duration to be very short to support a large population of active RFID tags.

J.2.2.1 Interoperability with the LRP UWB PHY

The LRP UWB PHYs characteristics have been deliberately chosen to be complementary to the (BPM/ BPSK) UWB PHY. They use the same center frequencies, both are impulse radio UWB PHYs and both can be implemented with coherent or non-coherent receivers. These characteristics allow a receiver architecture to be designed that can demodulate either type of PHY with maximal reuse of receiver blocks. This provides for interoperability shown in Figure J.3.

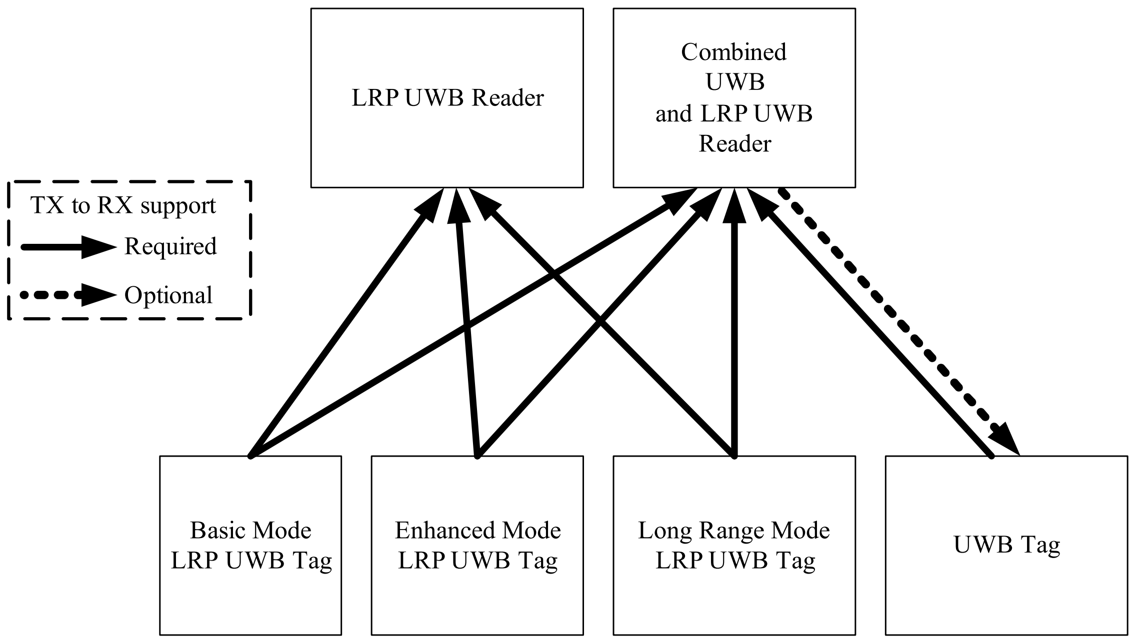

Figure J.3—LRP UWB PHY and UWB PHY interoperability

The UWB PHY is highly suitable for active RFID/RTLS systems based on time difference of arrival (TDOA). Indeed the choices available for its preamble length and data rate allow it to operate usefully in multiple scenarios. For instance, where long range is necessary a long preamble and the 110 kb/s data rate can be employed to maximize the range, or, where a higher density of tags and/or more frequent updates are needed, over a shorter range, the UWB PHY's high data rates and short preambles can be employed.

Readers that support demodulation of frames from tags employing the UWB PHY are facilitated to receive frames from LRP UWB tags by the alignment of the LRP UWB PHY band plan with channels 5, 6, 7, 9, and 11 of the UWB PHY. So for instance, in an integrated circuit supporting reception of the UWB PHY channel 5, which is 500 MHz centered at 6489.6 MHz, the analog portion can easily be capable of receiving the LRP UWB PHY channel 0, guaranteed to have at least 400 MHz bandwidth about 6489.6 MHz, its nominal frequency. In such an integrated circuit the digital decoding of the LRP modulation is a relatively small addition to make a device capable of supporting both UWB and LRP UWB modulations.

In mixed mode networks, it is required that the reader nodes be able to identify the modulation and appropriately demodulate it. For the LRP PHY the ability to do this is an integral part of this specification intended to be a base requirement for all its receivers as described in J.2.1.2. With the capability to support both UWB and LPF UWB PHYs, such universal UWB active RFID readers provide for a single infrastructure that simultaneously supports all these standard UWB active RFID/RTLS tags, see Figure J.3.

J.2.3 MSK PHY 2450 MHz band

J.2.3.1 Description

The MSK PHY 2450 MHz band is a narrowband PHY, operating in the band 2400 MHz to 2483.5 MHz and targeted at active RFID devices. It builds on the protocols used in traditional IEEE 802.15.4 systems, but the PHY uses non-spread-spectrum techniques that allow non-interfering operation in (typically industrial) sites where other 2.4 GHz ISM-band systems are already in use.

It can be used stand-alone for non-precision active RFID and data transfer applications or in conjunction with other IEEE 802.15.4 PHYs (e.g., LRP UWB PHY) for control and regulatory compliance. An example of a device that might use the LRP UWB PHY and the MSK PHY 2450 MHz band together is a small location tracking tag, which is operating in a regulatory domain that prohibits LRP UWB transmissions unless the tag is in the vicinity of a fixed reader infrastructure. The reader infrastructure might periodically transmit an “OK to transmit” signal via the MSK PHY 2450 MHz band, and the tag would inhibit its LRP UWB transmissions unless it had recently received such a signal.

J.2.3.2 Channel selection and interoperability with other 2.4 GHz services

The MSK PHY 2450 MHz band is compatible with global regulations relating to the 2.4 GHz ISM band and offers bidirectional capability with low circuit complexity, lower sidelobes than O-QPSK (leading to improved compatibility with neighboring users of the radio spectrum), and is implemented by commonly available transceiver ICs.

A typical target environment for the MSK PHY 2450 MHz band is an industrial site. These sites tend to have many existing systems (e.g., Wi-Fi®, ZigBee®) that use the 2.4 GHz ISM band. In these production environments, where frequency usage is carefully-planned, spectrum managers will insist that any new systems operate only on currently unused frequencies.[2]

Fortunately, in a typical environment of this kind, there tend to be small gaps in the RF spectrum, at the edges of the regions used by existing systems, where narrowband channels could coexist gracefully with those existing systems. The MSK PHY 2450 MHz band is designed with two key characteristics to support the use of these gaps, as follows:

- First, the channel bandwidth of the MSK PHY 2450 MHz band is small, because of its moderate data rate (250 kb/s) and its non-spread-spectrum nature.
- Second, the MSK PHY 2450 MHz band defines a large number of possible channels (42), so that it is likely that a suitable channel will fall in the region of the gap.

Furthermore, active RFID systems (for which the MSK PHY 2450 MHz band is targeted) tend to involve mobile active RFID tags and a fixed reader/control infrastructure. It is anticipated that frequency managers at these sites will select a set of suitable channels on which the MSK PHY 2450 MHz band can operate without causing interference to (or receiving interference from) existing systems.

One channel (channel page 7, channel number 47: 2463.75 MHz) is designated as a default channel.

J.2.3.3 Discovery and orphan recovery

Since devices (e.g., active RFID tags) may roam between sites and the configuration of a site may change, and since there are a large number of possible channels, it is necessary to consider how devices may determine the set of MSK PHY 2450 MHz band channels that are in use at a particular site, and how they can recover in the event that they lose contact with other devices in the system.

J.2.3.3.1 Tag initiated

It is expected that tags that are not associated with other devices in the system will search and/or beacon periodically on a subset of the MSK PHY 2450 MHz channels that are considered to be likely candidates for non-interference with common 2.4 GHz ISM services (e.g., Wi-Fi, ZigBee), in order to receive channel guidance from infrastructure and/or establish a connection to infrastructure. Once aware of any

[2]ZigBee is a registered trademark of the ZigBee Alliance. Wi-Fi is a registered trademark of the Wi-Fi Alliance. This information is given for the convenience of users of this standard and does not constitute an endorsement by the IEEE of this product. Equivalent products may be used if they can be shown to lead to the same results.

infrastructure operating on one of these channels (which may be a subset of the infrastructure at the site), the tag can determine the complete set of MSK PHY 2450 MHz channels that are in use at that site, either using information broadcast from the infrastructure or via a query/response mechanism, and direct its future channel selection activity appropriately.

NOTE—The precise subset of MSK PHY 2450 MHz channels that would be used for discovery is application-dependent and is out of the scope of this document.

In the case where a tag is operating on a particular MSK PHY 2450 MHz channel, it is expected that it will attempt to receive periodic messages on that channel from the surrounding infrastructure. If the tag fails to receive a number of these messages, it may conclude that either (a) it has been removed from the site, or (b) the configuration of the infrastructure has changed. In either case, it will likely revert to the discovery behavior detailed above.

J.2.3.3.2 Network initiated

It is expected that infrastructure at a particular site will beacon and/or listen periodically on a subset of the MSK PHY 2450 MHz channels that are considered to be likely candidates for non-interference with common 2.4 GHz ISM services (e.g., Wi-Fi, ZigBee), in order to provide channel selection guidance and/or establish a connection with tags at the site. Tags can then determine the complete set of MSK PHY 2450 MHz channels that are in use at that site, either using information in beacon messages from the infrastructure or via a query/response mechanism, and can then direct their future channel selection activity appropriately.

NOTE—The precise subset of MSK PHY 2450 MHz channels that would be used for discovery is application-dependent and is out of the scope of this document.

Infrastructure operating on a particular MSK PHY 2450 MHz channel may also send out channel selection or hand-off information to tags in the event that the infrastructure believes that a tag would be best served by the use of a different channel. This may occur, for example, when the link quality of a connection with a tag operating on a particular MSK PHY 2450 MHz channel tag is poor, when the tag is known to be physically at the edge of coverage of infrastructure operating on a particular MSK PHY 2450 MHz channel, or when the infrastructure knows that its own channel configuration is about to change (because of, say, system administration activity).

J.2.4 MSK PHY 433 MHz band

J.2.4.1 Description

The MSK PHY 433 MHz band is a narrowband PHY, operating in the band 433.05 MHz to 434.79 MHz, that targets active RFID/RTLS devices and systems where determination of presence and approximate position satisfies location requirements.

One of the primary characteristics of the MSK PHY 433 MHz band is a long communication range due to lower signal path loss when compared to other higher frequency PHYs within the IEEE 802.15™ family of protocols.

Its operation in frequency bands that are outside traditional IEEE 802® PHYs allows full independence and non-interfering operation in an environment where other IEEE 802 wireless protocols are used.

It can be used stand-alone for active RFID/RTLS, sensor and data transfer applications, or in conjunction with other IEEE 802.15.4 PHYs (e.g., LRP UWB PHY) for control and regulatory compliance.

The MSK PHY 433 MHz band is compatible with global regulations relating to the 433 MHz band, which is legal band in most of the countries. It offers bidirectional capability with low circuit complexity, mature and widely available silicon technology, which is low cost to implement because it takes advantage of existing investment in integrated circuits operating in a sub-GHz band.

The MSK PHY 433 MHz band uses MSK modulation, which has low side lobes, leading to more efficient usage of radio spectrum in this narrow frequency band and which can be implemented by commonly available transceivers.

J.2.4.2 Channel selection and data rates

The MSK PHY 433 MHz band uses 15 optional channels that use one of the following three data rates:

— 31.25 kb/s data rate provides additional 10 dB in receiver sensitivity at expense of longer RF packets.
— 100 kb/s provides the optimum data rate in cases in which a balanced combination of long range, channel occupancy, and power consumption is desired.
— 250 kb/s data rate can be used for applications where short RF packets minimize channel occupancy and power consumption at the expense of reduced communication range.

There are three 250 kb/s non-overlapping channels that occupy the entire 433 MHz band.

In addition to providing longer communication range, the 31.25 kb/s channel is optimized to comply with Japanese and Korean regulatory requirements.

J.2.4.3 433.92 MHz frequency

The 433.92 MHz frequency is a central frequency in 433 MHz band and in some regions of the world that is the only central frequency that can be used in this band. In order to allow compliance with these regulations, 433 MHz PHY can use all three data rates at this frequency.

J.2.4.4 Discovery and orphan recovery

Since devices (e.g., active RFID/RTLS tags) may roam between sites and the configuration of a site may change, and since there are a large number of possible channels, it is necessary to consider how devices may determine the set of channels or a single channel of MSK PHY 433 MHz band that are in use at a particular site, and how they can recover in the event that they lose contact with other devices in the system.

J.2.4.4.1 Tag initiated

It is expected that tags that are not associated with other devices in the system will search and/or beacon periodically on a default MSK PHY 433MHz band (channel 7), in order to receive channel guidance from infrastructure and/or establish a connection to infrastructure. Once aware of any infrastructure operating on one of these channels (which may be a subset of the infrastructure at the site), the tag can determine the complete set of MSK PHY 433 MHz channels that are in use at that site, either using information in beacon messages from the infrastructure or via a query/response mechanism, and direct its future channel selection activity appropriately.

In the case where a tag is operating on a particular MSK PHY 433 MHz channel, it is expected that it will attempt to receive periodic beacon messages on that channel from the surrounding infrastructure. If the tag fails to receive a number of these messages, it may conclude that either (a) it has been removed from the site, or (b) the configuration of the infrastructure has changed. In either case, it will likely revert to the discovery behavior detailed above.

It is expected that some of the devices compliant to MSK PHY 433 MHz band will not have RF receive capability (relying exclusively on ALOHA channel access). In such a case, other, alternative methods are used to set device channel at the time of device deployment (e.g., switch setting or other communication methods, unrelated to IEEE 802.15.4 PHYs), which would guarantee the most optimal operation of ALOHA channel access.

J.2.4.4.2 Network initiated

It is expected that infrastructure at a particular site will beacon and/or listen periodically on the default channel 7 of the MSK PHY 433 MHz band in order to discover nodes that are not associated in order to establish a connection. Nodes can then determine the complete set of MSK PHY 433 MHz channels that are in use at that site, by either using information in beacon messages from the infrastructure or via a query/response mechanism, and can then direct their future channel selection activity appropriately.

Infrastructure operating on a particular MSK PHY 433 MHz channel may also send out channel selection or hand-off information to nodes in the event that the infrastructure believes that a node would be best served by the use of a different channel. This may occur, for example, when the link quality of a connection with a node operating on a particular MSK PHY 433 MHz channel is poor, when the node is known to be physically at the edge of coverage of infrastructure operating on a particular MSK PHY 433 MHz channel, or when the infrastructure knows that its own channel configuration is about to change.

J.3 Overview of active RFID MAC features

The MAC requirements for active RFID are small. The main requirement for an active RFID tag is to transmit its ID number. A secondary requirement is to also provide a sequence number to aid in location determination for techniques that utilize time measurements. For IEEE 802.15.4 active RFID tags, the ID may be the device’s unique 64-bit address.

The application driving the active RFID tag periodically sends a message that includes an ID number uniquely identifying the sending tag. This periodic message is termed a *blink*. For maximum battery life the application layer will sleep in its lowest possible power state with its radio off, awaken briefly to send its blink message, and then return to its low power sleep state.

For lowest power consumption the blink frame should be as short as possible. The multipurpose blink frame is ideal for this purpose. Channel access using ALOHA is also a necessary part of the low power strategy in applications in which the active RFID tags are typically transmit-only and do not have a receiver capability to do carrier sensing. For ALOHA channel access to work well, the air-utilization of the network needs to be kept below 18%. This gives a good probability that tags’ transmissions get through to the reader infrastructure.

The MAC level primitive MCPS-DATA.request is used in LRP UWB and MSK PHY active RFID tag applications to initiate transmission of the multipurpose blink frame. This primitive allows selection of the preamble length, the data rate of the LRP UWB PHY that defines its modulation mode, and specification of the inclusion of a LEIP sequence. The selection of operating mode, preamble length, and inclusion of the LEIP depend on the on the capability of the PHY and the requirements of the application in terms of the desired operating range and the desired precision of any RTLS functionality.

The active RFID infrastructure consists of fixed location active RFID reader devices that receive the multipurpose blink frames sent by the active RFID tags. If a blink is received by multiple readers and then analyzed as a group at some central point, then localization may be possible.

The application driving the IEEE 802.15.4 active RFID reader then will typically initialize and permanently turn on the receiver to continually report the arrival of blink messages received from the active RFID tags.

The MAC level primitive MCPS-DATA.indication is used by the MAC layer in an active RFID reader to deliver details of any received multipurpose blink frames to the active RFID reader upper layers. This primitive contains the source address of the blink, which identifies the sending tag, and depending on the capabilities of the receiving PHY, additional parameters that can be used to perform an RTLS function when data from multiple readers is gathered at some central localization function. These additional parameters include angle-of-arrival, receive signal strength indication, and the time of arrival as provided by the *RangingCounterStop* parameter.

J.4 Location determination

J.4.1 Locating an object through received signal strength

A transmitting device (usually active RFID/RTLS tag) is transmitting a periodic signal (multipurpose blink frame) that is received by multiple readers. Each reader measures received signal strength during the PHY Header (Preamble and SFD) and produces an RSSI value (as specified in Table 48). Due to wide variations in antenna transmit patterns for small and inefficient antennas found in active RFID tags that can vary in size and form factor, the absolute value of RSSI cannot be relied upon for location determination. In order to compensate for this variation; RSSI values from multiple readers may be collected by an application on a centralized server and used to calculate approximate location of the transmitting device based on the relative RSSI values.

One of the methods to calculate location based on RSSI is "weighted center of mass" method where location is calculated based on known location of readers and RSSI values received by corresponding readers as in Equation (J.1):

$$X_{\mathrm{RSSI}} = \frac{\sum_{i=1}^{n} x_i r_i}{\sum_{i=1}^{n} r_i} \tag{J.1}$$

$$Y_{\mathrm{RSSI}} = \frac{\sum_{i=1}^{n} y_i r_i}{\sum_{i=1}^{n} r_i}$$

Where $x_i y_i$ define location of the reader and r_i is corresponding RSSI value for respective reader. Calculated values X_{RSSI} and Y_{RSSI} represent location of the transmitting device.

J.4.2 Locating an object through trilateration using time difference of arrival

J.4.2.1 Overview of trilateration

A transmitter (tag) sends a signal that is received by readers in at least three different locations. Each reader notes the signal's time-of-arrival (TOA). The difference in arrival times at any pair of readers implies that the transmitter was located somewhere on a known hyperbola. Using two reader pairs (one reader may be common between these pairs) implies that the tag resided at the intersection of two different hyperbolas. Figure J.4 illustrates this situation.

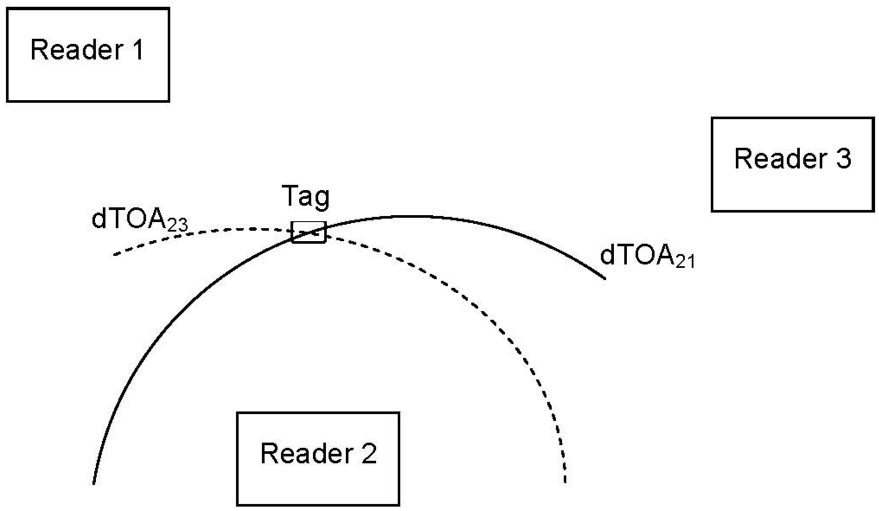

Figure J.4—Locating a tag through trilateration

Figure J.4 and the equations to follow all pertain to a two-dimensional (i.e., x, y) problem. If the tag is known to reside on some surface (e.g., in a pane or on a geoid) the equations can be readily modified to incorporate tag and reader elevation (z), without increasing the dimensionality of the solution. However, if tag elevation is unknown and to be evaluated, the equations must be altered to include z as a free variable and four readers will be required to produce a solution.

J.4.2.2 Mathematical location solution

Let t_x denote the time when the tag transmitted from location (x, y). The k^{th} reader, at location (x_k, y_k), will detect the signal at time $toa_k = t_x + p_k$ where p_k denotes the time required for the signal to propagate from the tag to the reader. This propagation time is equal to the tag-to-reader separation divided by the speed of light c as indicated in Equation (J.2):

$$p_k = \frac{\sqrt{(x - x_k)^2 + (y - y_k)^2}}{c} \tag{J.2}$$

The unknown transmission time becomes unimportant when considering the difference in arrival times at two readers ($dTOA_{jk}$) defined as shown in Equation (J.3):

$$dTOA_{jk} \equiv toa_j - toa_k = \frac{\sqrt{(x - x_j)^2 + (y - y_j)^2}}{c} - \frac{\sqrt{(x - x_k)^2 + (y - y_k)^2}}{c} \tag{J.3}$$

Equation (J.3) was used to generate the hyperbolic segments shown in Figure J.4 for both $dTOA_{21}$ and $dTOA_{23}$.

The following subclause details a method of solving for the intersection of these two hyperbolas. Equation pair will produce two possible locations for this intersection, one real and the other (almost always) extraneous. An extraneous solution will not satisfy the original pair of $dTOA$ equations and may be recognized by this failure.

J.4.2.3 Detailed equation derivation

For convenience, define $\delta_{jk} \equiv c \cdot dTOA_{jk}$. By squaring Equation (J.3) and collecting terms, one obtains the relationship shown in Equation (J.4):

$$\frac{1}{2}\{\delta_{jk}{}^2 + (x_j{}^2 - y_k{}^2) - (x_k{}^2 - y_j{}^2)\} + (x_k - x_j) \cdot x + (y_k - y_j) \cdot y = \delta_{jk} \cdot \sqrt{(x - x_j)^2 + (y - y_j)^2} \tag{J.4}$$

Again, to simplify notation define $\lambda_{jk} \equiv ½ \{ \delta_{jk}{}^2 + (x_j{}^2 - y_k{}^2) - (x_k{}^2 - y_j{}^2) \}$, then readers 1, 2, and 3 give the hyperbolic relationships shown in Equation (J.5a) and Equation (J.5b):

$$\lambda_{21} + (x_1 - x_2) \cdot x + (y_1 - y_2) \cdot y = \delta_{21} \cdot \sqrt{(x - x_2)^2 + (y - y_2)^2} \tag{J.5a}$$

$$\lambda_{23} + (x_3 - x_2) \cdot x + (y_3 - y_2) \cdot y = \delta_{23} \cdot \sqrt{(x - x_2)^2 + (y - y_2)^2} \tag{J.5b}$$

Subtracting these two shows that the location solution must lie on a line given by Equation (J.6):

$$\{\delta_{23} \cdot (y_1 - y_2) - \delta_{21} \cdot (y_3 - y_2)\} \cdot y + \{\delta_{23} \cdot (x_1 - x_2) - \delta_{21} \cdot (x_3 - x_2)\} \cdot y + (\delta_{23} \cdot \lambda_{21} - \delta_{21} \cdot \lambda_{23}) = 0, \tag{J.6}$$

Or equivalently $y = m \cdot x + b$ where, as shown in Equation (J.7a) and Equation (J.7b):

$$m = -\frac{\delta_{23} \cdot (x_1 - x_2) - \delta_{21} \cdot (x_3 - x_2)}{\delta_{23} \cdot (y_1 - y_2) - \delta_{21} \cdot (y_3 - y_2)} \tag{J.7a}$$

$$b = -\frac{\delta_{23} \cdot \lambda_{21} - \delta_{21} \cdot \lambda_{23}}{\delta_{23} \cdot (y_1 - y_2) - \delta_{21} \cdot (y_3 - y_2)} \tag{J.7b}$$

All that remains is to find the intersection of this line with either of the previously identified hyperbolas. Substituting $y = m \cdot x + b$ into hyperbolic relationship Equation (J.5a) and Equation (J.5b), squaring and collecting terms gives the quadratic equation $A \cdot x^2 + B \cdot x + C = 0$ where, as shown in Equation (J.8a), Equation (J.8b), and Equation (J.8c):

$$A = (x_1 - x_2)^2 + 2 \cdot m \cdot (x_1 - x_2) \cdot (y_1 - y_2) + m^2 \cdot (y_1 - y_2)^2 - \delta_{21}{}^2 \cdot (1 + m^2), \tag{J.8a}$$

$$\begin{aligned} B = 2 \cdot \{&\lambda_{21} \cdot (x_1 - x_2) + \lambda_{21} \cdot m \cdot (y_1 - y_2) + b \cdot (x_1 - x_2) \cdot (y_1 - y_2) + m \cdot b \cdot (y_1 - y_2)^2 + \\ &\delta_{21}{}^2 \cdot (x_2 - m \cdot b + m \cdot y_2)\}, \end{aligned} \tag{J.8b}$$

$$C = \lambda_{21}{}^2 + 2 \cdot \lambda_{21} \cdot b \cdot (y_1 - y_2) + b^2 \cdot (y_1 - y_2)^2 - \delta_{21}{}^2 \cdot (x_2{}^2 + (b - y_2)^2). \tag{J.8c}$$

Two possible solutions for the tag location are given by the quadratic formula along with the linear equation shown in Equation (J.9a) and Equation (J.9b):

$$x = \frac{-B \pm \sqrt{B^2 - 4 \cdot A \cdot C}}{2 \cdot A} \quad \text{(J.9a)}$$

$$y = m \cdot x + b \quad \text{(J.9b)}$$

The second solution to the pair of equations [Equation (J.9a) and Equation (J.9b)] is (almost always) extraneous, introduced by the squaring operation. It can be recognized by the fact that it will not match the observed time differences.

J.4.3 Locating an object through angle of arrival

J.4.3.1 Overview of triangulation

A transmitter (tag) sends a signal that is received by readers in (at least) two different locations. Each reader notes the signal's angle-of-arrival (AOA), in azimuth, elevation or both. The tag resides at the intersection of the angle vectors measured at two readers, as shown in Figure J.5:

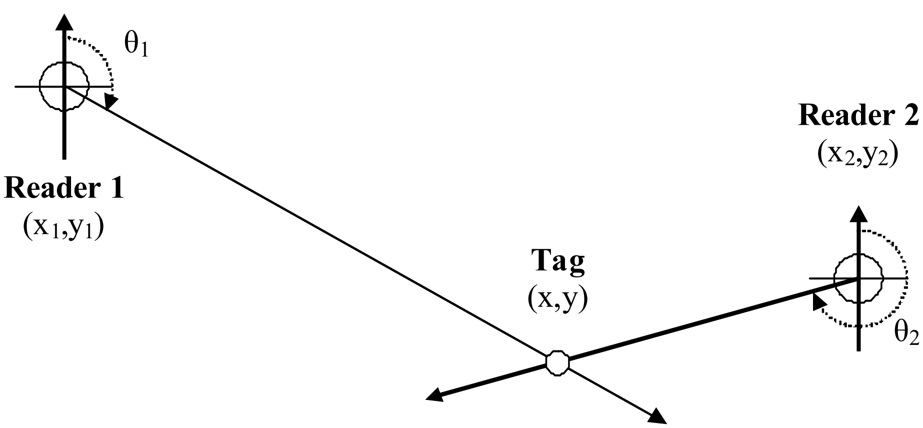

Figure J.5—Locating a tag through triangulation

If both azimuth and elevation are measured at each reader (Figure J.5 shows only one measurement being made at each reader) then it is possible to find the 3D location of the tag using information from only two readers.

J.4.3.2 Mathematical location solution

In Figure J.5, the tag position (x,y) can be calculated using Equation (J.10) and Equation (J.11):

d_1 (distance from Reader 1 to Tag) = $\mathrm{sqrt}((x - x_1)^2 + (y - y_1)^2)$ (J.10)

d_2 (distance from Reader 2 to Tag) = $\mathrm{sqrt}((x - x_2)^2 + (y - y_2)^2)$ (J.11)

Then:

$x = x_1 + d_1 \times \sin(\theta_1)$

$y = y_1 + d_1 \times \cos(\theta_1)$

And also:

$x = x_2 + d_2 \times \sin(\theta_2)$

$y = y_2 + d_2 \times \cos(\theta_2)$

These equations can be solved to determine the two unknowns (x,y) using the two measurements θ_1 and θ_2.