6. PHY specification

This clause specifies four PHY options for IEEE 802.15.4. The PHY is responsible for the following tasks:

— Activation and deactivation of the radio transceiver
— ED within the current channel
— LQI for received packets
— CCA for CSMA-CA
— Channel frequency selection
— Data transmission and reception

Constants and attributes that are specified and maintained by the PHY are written in the text of this clause in italics. Constants have a general prefix of "a", e.g., *aMaxPHYPacketSize*, and are listed in Table 19. Attributes have a general prefix of "phy", e.g., *phyCurrentChannel*, and are listed in Table 20.

6.1 General requirements and definitions

This subclause specifies requirements that are common to all of the IEEE 802.15.4 PHYs.

6.1.1 Operating frequency range

A compliant device shall operate in one or several frequency bands using the modulation and spreading formats summarized in Table 1.

Table 1—Frequency bands and data rates

PHY (MHz)	Frequency band (MHz)	Spreading parameters		Data parameters		
		Chip rate (kchip/s)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbol/s)	Symbols
868/915	868–868.6	300	BPSK	20	20	Binary
	902–928	600	BPSK	40	40	Binary
868/915 alternate	868–868.6	440	PSSS	206	13.75	15-ary
	902–928	1600	PSSS	250	62.5	5-ary
868/915 alternate	868–868.6	400	O-QPSK	100	25	16-ary Orthogonal
	902–928	1000	O-QPSK	250	62.5	16-ary Orthogonal
2450	2400–2483.5	2000	O-QPSK	250	62.5	16-ary Orthogonal

This standard is intended to conform with established regulations in Europe, Japan, Canada, and the United States. The regulatory documents listed below are for information only and are subject to change and revisions at any time. IEEE 802.15.4 devices shall also comply with specific regional legislation. Additional regulatory information is provided in Annex F.

Europe:

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- Approval standards: European Telecommunications Standards Institute (ETSI)
- Documents: ETSI EN 300 328-1 [B11][6], ETSI EN 300 328-2 [B12], ETSI EN 300 220-1 [B10], ERC 70-03 [B13]
- Approval authority: National type approval authorities

Japan:

- Approval standards: Association of Radio Industries and Businesses (ARIB)
- Document: ARIB STD-T66 [B14]
- Approval authority: Ministry of Public Management, Home Affairs, Posts and Telecommunications (MPHPT)

United States:

- Approval standards: Federal Communications Commission (FCC), United States
- Document: FCC CFR47, Section 15.247 [B14]

Canada:

- Approval standards: Industry Canada (IC), Canada
- Document: GL36 [B15]

6.1.2 Channel assignments and numbering

A total of 27 channels, numbered 0 to 26, are available across the three frequency bands. Sixteen channels are available in the 2450 MHz band, 10 in the 915 MHz band, and 1 in the 868 MHz band. The center frequency of these channels is defined as follows:

$$F_c = 868.3 \text{ in megahertz, for } k = 0$$

$$F_c = 906 + 2\,(k - 1) \text{ in megahertz, for } k = 1, 2, ..., 10$$

and $$F_c = 2405 + 5\,(k - 11) \text{ in megahertz, for } k = 11, 12, ..., 26$$

where

k is the channel number.

For each PHY supported, a compliant device shall support all channels allowed by regulations for the region in which the device operates.

6.1.2.1 Channel pages

The introduction of the “868/915 MHz band enhanced PSSS alternate PHY specifications” and “868/915 MHz band enhanced O-QPSK alternate PHY specifications” results in the total number of channel numbers exceeding the current channel numbering capability of 32 channel numbers.

The upper 5 MSBs, which are currently reserved, of 32 bit channel bitmap will be used as an integer value to specify 32 channel pages. The lower 27 bits of the channel bit map will be used a bit mask to specify a channel number within the page identifed by the integer representation of the upper 5 MSB’s.

The channel page and channel numbering are shown in Table 2.

[6]The numbers in brackets correspond to the numbers of the bibliography in Annex G.

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Table 2—Channel page and numbering

Channel page (decimal)	Channel page (binary) (b_{31}, b_{30}, b_{29}, b_{28}, b_{27})	Channel number(s) (decimal)	Channel number description
0	0 0 0 0 0	0	Channel 0 is in 868 MHz band using BPSK
		1 - 10	Channels 1 to 10 are in 915 MHz band using BPSK
		11 - 26	Channels 11 to 26 are in 2.4 GHz band using O-QPSK
1	0 0 0 0 1	0	Channel 0 is in 868 MHz band using PSSS
		1 - 10	Channels 1 to 10 are in 915 MHz band using PSSS
2	0 0 0 1 0	0	Channel 0 is in 868 MHz band using O-QPSK
		1 - 10	Channels 1 to 10 are in 915 MHz band using O-QPSK
3	0 0 0 1 1	reserved	reserved
4	0 0 1 0 0	reserved	reserved
5	0 0 1 0 1	reserved	reserved
6	0 0 1 1 0	reserved	reserved
7	0 0 1 1 1	reserved	reserved
8	0 1 0 0 0	reserved	reserved
9	0 1 0 0 1	reserved	reserved
10	0 1 0 1 0	reserved	reserved
11	0 1 0 1 1	reserved	reserved
12	0 1 1 0 0	reserved	reserved
13	0 1 1 0 1	reserved	reserved
14	0 1 1 1 0	reserved	reserved
15	0 1 1 1 1	reserved	reserved
16	1 0 0 0 0	reserved	reserved
17	1 0 0 0 1	reserved	reserved
18	1 0 0 1 0	reserved	reserved
19	1 0 0 1 1	reserved	reserved
20	1 0 1 0 0	reserved	reserved
21	1 0 1 0 1	reserved	reserved
22	1 0 1 1 0	reserved	reserved
23	1 0 1 1 1	reserved	reserved
24	1 1 0 0 0	reserved	reserved
25	1 1 0 0 1	reserved	reserved

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Table 2—Channel page and numbering

26	1 1 0 1 0	reserved	reserved
27	1 1 0 1 1	reserved	reserved
28	1 1 1 0 0	reserved	reserved
29	1 1 1 0 1	reserved	reserved
30	1 1 1 1 0	reserved	reserved
31	1 1 1 1 1	reserved	reserved

For example, the bitmap for Chan nel 3 of Channel page 3 would be:

0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0

Channel pages 3 to 31 are reserved for future definition. New pages will also a have fixed logical channel to physical frequency and modulation scheme mapping like Channel page 0. Each channel page may have up to 27 channels.

To support the use of the channel page and channel numbering scheme 2 new PHY PIB attributes, *phyPagesSupported* and *phyCurrentPage*, will have to be added to Table 20 (PHY PIB attributes). In addition to this the PHY PIB attribute *phyChannelSupported* will be modified. The description of the 2 new PHY PIB attributes and the modification of the current PHY PIB attribute will be described in 6.4.2.

6.1.3 RF power measurement

Unless otherwise stated, all RF power measurements, either transmit or receive, shall be made at the appropriate transceiver to antenna connector. The measurements shall be made with equipment that is either matched to the impedance of the antenna connector or corrected for any mismatch. For devices without an antenna connector, the measurements shall be interpreted as effective isotropic radiated power (EIRP) (i.e., a 0 dBi gain antenna); and any radiated measurements shall be corrected to compensate for the antenna gain in the implementation.

6.1.4 Transmit power

The maximum transmit power shall conform with local regulations. Refer to Annex F for additional information on regulatory limits. A compliant device shall have its nominal transmit power level indicated by its PHY parameter, *phyTransmitPower* (see 6.4).

6.1.5 Out-of-band spurious emission

The out-of-band spurious emissions shall conform with local regulations. Refer to Annex F for additional information on regulatory limits on out-of-band emissions.

6.1.6 Receiver sensitivity definitions

The definitions in Table 3 are referenced by subclauses elsewhere in this standard regarding receiver sensitivity.

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Table 3—Receiver sensitivity definitions

Term	Definition of term	Conditions
Packet error rate (PER)	Average fraction of transmitted packets that are not detected correctly.	– Average measured over random PSDU data.
Receiver sensitivity	Threshold input signal power that yields a specified PER.	– PSDU length = 20 octets. – PER < 1%. – Power measured at antenna terminals. – Interference not present.

6.2 PHY service specifications

The PHY provides an interface between the MAC sublayer and the physical radio channel, via the RF firmware and RF hardware. The PHY conceptually includes a management entity called the PLME. This entity provides the layer management service interfaces through which layer management functions may be invoked. The PLME is also responsible for maintaining a database of managed objects pertaining to the PHY. This database is referred to as the PHY PAN information base (PIB).

Figure 15 depicts the components and interfaces of the PHY.

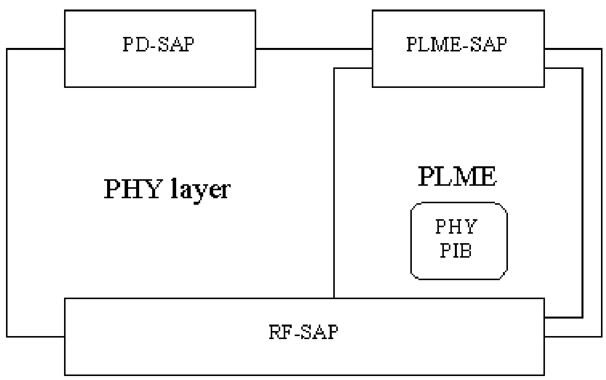

Figure 15—The PHY reference model

The PHY provides two services, accessed through two SAPs: the PHY data service, accessed through the PHY data SAP (PD-SAP), and the PHY management service, accessed through the PLME's SAP (PLME-SAP).

6.2.1 PHY data service

The PD-SAP supports the transport of MPDUs between peer MAC sublayer entities. Table 4 lists the primitives supported by the PD-SAP. These primitives are discussed in the subclauses referenced in the table.

6.2.1.1 PD-DATA.request

The PD-DATA.request primitive requests the transfer of an MPDU (i.e., PSDU) from the MAC sublayer to the local PHY entity.

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Table 4—PD-SAP primitives

PD-SAP primitive	Request	Confirm	Indication
PD-DATA	6.2.1.1	6.2.1.2	6.2.1.3

6.2.1.1.1 Semantics of the service primitive

The semantics of the PD-DATA.request primitive is as follows:

```
PD-DATA.request          (
                         psduLength,
                         psdu
                         )
```

Table 5 specifies the parameters for the PD-DATA.request primitive.

Table 5—PD-DATA.request parameters

Name	Type	Valid range	Description
psduLength	Unsigned Integer	≤ *aMaxPHYPacketSize*	The number of octets contained in the PSDU to be transmitted by the PHY entity.
psdu	Set of octets	—	The set of octets forming the PSDU to be transmitted by the PHY entity.

6.2.1.1.2 When generated

The PD-DATA.request primitive is generated by a local MAC sublayer entity and issued to its PHY entity to request the transmission of an MPDU.

6.2.1.1.3 Effect on receipt

The receipt of the PD-DATA.request primitive by the PHY entity will cause the transmission of the supplied PSDU. Provided the transmitter is enabled (TX_ON state), the PHY will first construct a PPDU, containing the supplied PSDU, and then transmit the PPDU. When the PHY entity has completed the transmission, it will issue the PD-DATA.confirm primitive with a status of SUCCESS.

If the PD-DATA.request primitive is received while the receiver is enabled (RX_ON state) the PHY entity will issue the PD-DATA.confirm primitive with a status of RX_ON. If the PD-DATA.request primitive is received while the transceiver is disabled (TRX_OFF state), the PHY entity will issue the PD-DATA.confirm primitive with a status of TRX_OFF. If the PD-DATA.request primitive is received while the transmitter is already busy transmittng (BUSY_TX state) the PHY entity will issue the PD-DATA.confirm primitive with a status of BUSY_TX.

6.2.1.2 PD-DATA.confirm

The PD-DATA.confirm primitive confirms the end of the transmission of an MPDU (i.e., PSDU) from a local MAC sublayer entity to a peer MAC sublayer entity.

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6.2.1.2.1 Semantics of the service primitive

The semantics of the PD-DATA.confirm primitive is as follows:

```
PD-DATA.confirm          (
                          status
                          )
```

Table 6 specifies the parameters for the PD-DATA.confirm primitive.

Table 6—PD-DATA.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	SUCCESS, RX_ON, TRX_OFF, or BUSY_TX	The result of the request to transmit a packet.

6.2.1.2.2 When generated

The PD-DATA.confirm primitive is generated by the PHY entity and issued to its MAC sublayer entity in response to a PD-DATA.request primitive. The PD-DATA.confirm primitive will return a status of either SUCCESS, indicating that the request to transmit was successful, or an error code of RX_ON, TRX_OFF or BUSY_TX. The reasons for these status values are fully described in 6.2.1.1.3.

6.2.1.2.3 Effect on receipt

On receipt of the PD-DATA.confirm primitive, the MAC sublayer entity is notified of the result of its request to transmit. If the transmission attempt was successful, the status parameter is set to SUCCESS. Otherwise, the status parameter will indicate the error.

6.2.1.3 PD-DATA.indication

The PD-DATA.indication primitive indicates the transfer of an MPDU (i.e., PSDU) from the PHY to the local MAC sublayer entity.

6.2.1.3.1 Semantics of the service primitive

The semantics of the PD-DATA.indication primitive is as follows:

```
PD-DATA.indication       (
                          psduLength,
                          psdu,
                          ppduLinkQuality
                          )
```

Table 7 specifies the parameters for the PD-DATA.indication primitive.

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Table 7—PD-DATA.indication parameters

Name	Type	Valid range	Description
psduLength	Unsigned Integer	≤ *aMaxPHYPacketSize*	The number of octets contained in the PSDU received by the PHY entity.
psdu	Set of octets	—	The set of octets forming the PSDU received by the PHY entity.
ppduLinkQuality	Integer	0 x 00–0 x ff	Link quality (LQ) value measured during reception of the PPDU (see 6.9.8).

6.2.1.3.2 When generated

The PD-DATA.indication primitive is generated by the PHY entity and issued to its MAC sublayer entity to transfer a received PSDU. This primitive will not be generated if the received psduLength field is zero or greater than *aMaxPHYPacketSize*.

6.2.1.3.3 Effect on receipt

On receipt of the PD-DATA.indication primitive, the MAC sublayer is notified of the arrival of an MPDU across the PHY data service.

6.2.2 PHY management service

The PLME-SAP allows the transport of management commands between the MLME and the PLME. Table 8 lists the primitives supported by the PLME-SAP. These primitives are discussed in the clauses referenced in the table.

Table 8—PLME-SAP primitives

PLME-SAP primitive	Request	Confirm
PLME-CCA	6.2.2.1	6.2.2.2
PLME-ED	6.2.2.3	6.2.2.4
PLME-GET	6.2.2.5	6.2.2.6
PLME-SET-TRX-STATE	6.2.2.7	6.2.2.8
PLME-SET	6.2.2.9	6.2.2.10

6.2.2.1 PLME-CCA.request

The PLME-CCA.request primitive requests that the PLME perform a CCA as defined in 6.9.9.

6.2.2.1.1 Semantics of the service primitive

The semantics of the PLME-CCA.request primitive is as follows:

PLME-CCA.request ()

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There are no parameters associated with the PLME-CCA.request primitive.

6.2.2.1.2 When generated

The PLME-CCA.request primitive is generated by the MLME and issued to its PLME whenever the CSMA-CA algorithm requires an assessment of the channel.

6.2.2.1.3 Effect on receipt

If the receiver is enabled on receipt of the PLME-CCA.request primitive, the PLME will cause the PHY to perform a CCA. When the PHY has completed the CCA, the PLME will issue the PLME-CCA.confirm primitive with a status of either BUSY or IDLE, depending on the result of the CCA.

If the PLME-CCA.request primitive is received while the transceiver is disabled (TRX_OFF state) or if the transmitter is enabled (TX_ON state), the PLME will issue the PLME-CCA.confirm primitive with a status of TRX_OFF or TX_ON, respectively.

6.2.2.2 PLME-CCA.confirm

The PLME-CCA.confirm primitive reports the results of a CCA.

6.2.2.2.1 Semantics of the service primitive

The semantics of the PLME-CCA.confirm primitive is as follows:

```
PLME-CCA.confirm        (
                        status
                        )
```

Table 9 specifies the parameters for the PLME-CCA.confirm primitive.

Table 9—PLME-CCA.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	TRX_OFF, TX_ON, BUSY, or IDLE	The result of the request to perform a CCA.

6.2.2.2.2 When generated

The PLME-CCA.confirm primitive is generated by the PLME and issued to its MLME in response to a PLME-CCA.request primitive. The PLME-CCA.confirm primitive will return a status of either BUSY or IDLE, indicating a successful CCA, or an error code of TRX_OFF or TX_ON. The reasons for these status values are fully described in 6.2.2.1.3.

6.2.2.2.3 Effect on receipt

On receipt of the PLME-CCA.confirm primitive, the MLME is notified of the results of the CCA. If the CCA attempt was successful, the status parameter is set to either BUSY or IDLE. Otherwise, the status parameter will indicate the error.

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6.2.2.3 PLME-ED.request

The PLME-ED.request primitive requests that the PLME perform an ED measurement (see 6.9.7).

6.2.2.3.1 Semantics of the service primitive

The semantics of the PLME-ED.request primitive is as follows:

PLME-ED.request ()

There are no parameters associated with the PLME-ED.request primitive.

6.2.2.3.2 When generated

The PLME-ED.request primitive is generated by the MLME and issued to its PLME to request an ED measurement.

6.2.2.3.3 Effect on receipt

If the receiver is enabled on receipt of the PLME-ED.request primitive, the PLME will cause the PHY to perform an ED measurement. When the PHY has completed the ED measurement, the PLME will issue the PLME-ED.confirm primitive with a status of SUCCESS.

If the PLME-ED.request primitive is received while the transceiver is disabled (TRX_OFF state) or if the transmitter is enabled (TX_ON state), the PLME will issue the PLME-ED.confirm primitive with a status of TRX_OFF or TX_ON, respectively.

6.2.2.4 PLME-ED.confirm

The PLME-ED.confirm primitive reports the results of the ED measurement.

6.2.2.4.1 Semantics of the service primitive

The semantics of the PLME-ED.confirm primitive is as follows:

```
PLME-ED.confirm          (
                         status,
                         EnergyLevel
                         )
```

Table 10 specifies the parameters for the PLME-ED.confirm primitive.

Table 10—PLME-ED.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	SUCCESS, TRX_OFF, or TX_ON	The result of the request to perform an ED measurement.
EnergyLevel	Integer	0 x 00–0 x ff	ED level for the current channel.

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6.2.2.4.2 When generated

The PLME-ED.confirm primitive is generated by the PLME and issued to its MLME in response to a PLME-ED.request primitive. The PLME-ED.confirm primitive will return a status of SUCCESS, indicating a successful ED measurement, or an error code of TRX_OFF or TX_ON. The reasons for these status values are fully described in 6.2.2.3.3.

6.2.2.4.3 Effect on receipt

On receipt of the PLME-ED.confirm primitive, the MLME is notified of the results of the ED measurement. If the ED measurement attempt was successful, the status parameter is set to SUCCESS. Otherwise, the status parameter will indicate the error.

6.2.2.5 PLME-GET.request

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

6.2.2.5.1 Semantics of the service primitive

The semantics of the PLME-GET.request primitive is as follows:

```
PLME-GET.request                (
                                PIBAttribute
                                )
```

Table 11 specifies the parameters for the PLME-GET.request primitive.

Table 11—PLME-GET.request parameters

Name	Type	Valid range	Description
PIBAttribute	Enumeration	See Table 20	The identifier of the PHY PIB attribute to get.

6.2.2.5.2 When generated

The PLME-GET.request primitive is generated by the MLME and issued to its PLME to obtain information from the PHY PIB.

6.2.2.5.3 Effect on receipt

On receipt of the PLME-GET.request primitive, the PLME will attempt to retrieve the requested PHY PIB attribute from its database. If the identifier of the PIB attribute is not found in the database, the PLME will issue the PLME-GET.confirm primitive with a status of UNSUPPORTED_ATTRIBUTE.

If the requested PHY PIB attribute is successfully retrieved, the PLME will issue the PLME-GET.confirm primitive with a status of SUCCESS.

6.2.2.6 PLME-GET.confirm

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

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6.2.2.6.1 Semantics of the service primitive

The semantics of the PLME-GET.confirm primitive is as follows:

```
PLME-GET.confirm          (
                          status,
                          PIBAttribute,
                          PIBAttributeValue
                          )
```

Table 12 specifies the parameters for the PLME-GET.confirm primitive.

Table 12—PLME-GET.confirm parameters

Name	Type	Valid range	Description
Status	Enumeration	SUCCESS or UNSUPPORTED_ATTRIBUTE	The result of the request for PHY PIB attribute information.
PIBAttribute	Enumeration	See Table 20	The identifier of the PHY PIB attribute to get.
PIBAttributeValue	Various	Attribute specific	The value of the indicated PHY PIB attribute to get. This parameter has zero length when the Status parameter is set to UNSUPPORTED_ATTRIBUTE.

6.2.2.6.2 When generated

The PLME-GET.confirm primitive is generated by the PLME and issued to its MLME in response to a PLME-GET.request primitive. The PLME-GET.confirm primitive will return a status of either SUCCESS, indicating that the request to read a PHY PIB attribute was successful, or an error code of UNSUPPORTED_ATTRIBUTE. When an error code of UNSUPPORTED_ATTRIBUTE is returned the PIBAttributeValue parameter will be set to length zero. The reasons for these status values are fully described in subclause 6.2.2.5.3.

6.2.2.6.3 Effect on receipt

On receipt of the PLME-GET.confirm primitive, the MLME is notified of the results of its request to read a PHY PIB attribute. If the request to read a PHY PIB attribute was successful, the status parameter is set to SUCCESS. Otherwise, the status parameter will indicate the error.

6.2.2.7 PLME-SET-TRX-STATE.request

The PLME-SET-TRX-STATE.request primitive requests that the PHY entity change the internal operating state of the transceiver. The transceiver will have three main states:

— Transceiver disabled (TRX_OFF).
— Transmitter enabled (TX_ON).
— Receiver enabled (RX_ON).

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6.2.2.7.1 Semantics of the service primitive

The semantics of the PLME-SET-TRX-STATE.request primitive is as follows:

```
PLME-SET-TRX-STATE.request      (
                                state
                                )
```

Table 13 specifies the parameters for the PLME-SET-TRX-STATE.request primitive.

Table 13—PLME-SET-TRX-STATE.request parameters

Name	Type	Valid range	Description
state	Enumeration	RX_ON, TRX_OFF, FORCE_TRX_OFF, or TX_ON	The new state in which to configure the transceiver.

6.2.2.7.2 When generated

The PLME-SET-TRX-STATE.request primitive is generated by the MLME and issued to its PLME when the current operational state of the receiver needs to be changed.

6.2.2.7.3 Effect on receipt

On receipt of the PLME-SET-TRX-STATE.request primitive, the PLME will cause the PHY to change to the requested state. If the state change is accepted, the PHY will issue the PLME-SET-TRX-STATE.confirm primitive with a status of SUCCESS. If this primitive requests a state that the transceiver is already configured, the PHY will issue the PLME-SET-TRX-STATE.confirm primitive with a status indicating the current state, i.e., RX_ON, TRX_OFF, or TX_ON. If this primitive is issued with RX_ON or TRX_OFF argument and the PHY is busy transmitting a PPDU, the PHY will issue the PLME-SET-TRX-STATE.confirm primitive with a status BUSY_TX and defer the state change till the end of transmission. If this primitive is issued with TX_ON or TRX_OFF argument and the PHY is in RX_ON state and has already received a valid SFD, the PHY will issue the PLME-SET-TRX-STATE.confirm primitive with a status BUSY_RX and defer the state change till the end of reception of the PPDU. If this primitive is issued with FORCE_TRX_OFF, the PHY will cause the PHY to go the TRX_OFF state irrespective of the state the PHY is in.

6.2.2.8 PLME-SET-TRX-STATE.confirm

The PLME-SET-TRX-STATE.confirm primitive reports the result of a request to change the internal operating state of the transceiver.

6.2.2.8.1 Semantics of the service primitive

The semantics of the PLME-SET-TRX-STATE.confirm primitive is as follows:

```
PLME-SET-TRX-STATE.confirm      (
                                status
                                )
```

Table 14 specifies the parameters for the PLME-SET-TRX-STATE.confirm primitive.

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Table 14—PLME-SET-TRX-STATE.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	SUCCESS, RX_ON, TRX_OFF, TX_ON, BUSY_RX, or BUSY_TX	The result of the request to change the state of the transceiver.

6.2.2.8.2 When generated

The PLME-SET-TRX-STATE.confirm primitive is generated by the PLME and issued to its MLME after attempting to change the internal operating state of the transceiver.

6.2.2.8.3 Effect on receipt

On receipt of the PLME-SET-TRX-STATE.confirm primitive, the MLME is notified of the result of its request to change the internal operating state of the transceiver. A status value of SUCCESS indicates that the internal operating state of the transceiver was accepted. A status value of RX_ON, TRX_OFF, or TX_ON indicates that the transceiver is already in the requested internal operating state. A status value of BUSY_TX is issued when the PHY is requested to change its state to RX_ON or TRX_OFF while transmitting. A status value of BUSY_RX is issued when the PHY is in RX_ON state, has already received a valid SFD, and is requested to change its state to TX_ON or TRX_OFF.

6.2.2.9 PLME-SET.request

The PLME-SET.request primitive attempts to set the indicated PHY PIB attribute to the given value.

6.2.2.9.1 Semantics of the service primitive

The semantics of the PLME-SET.request primitive is as follows:

```
PLME-SET.request          (
                          PIBAttribute,
                          PIBAttributeValue
                          )
```

Table 15 specifies the parameters for the PLME-SET.request primitive.

Table 15—PLME-SET.request parameters

Name	Type	Valid range	Description
PIBAttribute	Enumeration	See Table 20	The identifier of the PIB attribute to set.
PIBAttributeValue	Various	Attribute specific	The value of the indicated PIB attribute to set.

6.2.2.9.2 When generated

The PLME-SET.request primitive is generated by the MLME and issued to its PLME to write the indicated PHY PIB attribute.

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6.2.2.9.3 Effect on receipt

On receipt of the PLME-SET.request primitive, the PLME will attempt to write the given value to the indicated PHY PIB attribute in its database. If the PIBAttribute parameter specifies an attribute that is not found in the database (see Table 20), the PLME will issue the PLME-SET.confirm primitive with a status of UNSUPPORTED_ATTRIBUTE. If the PIBAttibuteValue parameter specifies a value that is out of the valid range for the given attribute, the PLME will issue the PLME-SET.confirm primitive with a status of INVALID_PARAMETER.

If the requested PHY PIB attribute is successfully written, the PLME will issue the PLME-SET.confirm primitive with a status of SUCCESS.

6.2.2.10 PLME-SET.confirm

The PLME-SET.confirm primitive reports the results of the attempt to set a PIB attribute.

6.2.2.10.1 Semantics of the service primitive

The semantics of the PLME-SET.confirm primitive is as follows:

```
PLME-SET.confirm          (
                          status,
                          PIBAttribute
                          )
```

Table 16 specifies the parameters for the PLME-SET.confirm primitive.

Table 16—PLME-SET.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	SUCCESS, UNSUPPORTED_ATTRIBUTE, or INVALID_PARAMETER	The status of the attempt to set the request PIB attribute.
PIBAttribute	Enumeration	See Table 20	The identifier of the PIB attribute being confirmed.

6.2.2.10.2 When generated

The PLME-SET.confirm primitive is generated by the PLME and issued to its MLME in response to a PLME-SET.request primitive. The PLME-SET.confirm primitive will return a status of either SUCCESS, indicating that the requested value was written to the indicated PHY PIB attribute, or an error code of UNSUPPORTED_ATTRIBUTE or INVALID_PARAMETER. The reasons for these status values are fully described in subclause 6.2.2.9.3.

6.2.2.10.3 Effect on receipt

On receipt of the PLME-SET.confirm primitive, the MLME is notified of the result of its request to set the value of a PHY PIB attribute. If the requested value was written to the indicated PHY PIB attribute, the status parameter is set to SUCCESS. Otherwise, the status parameter will indicate the error.

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6.2.3 PHY enumerations description

Table 17 shows a description of the PHY enumeration values defined in the PHY specification.

Table 17—PHY enumerations description

Enumeration	Value	Description
BUSY	0 x 00	The CCA attempt has detected a busy channel.
BUSY_RX	0 x 01	The transceiver is asked to change its state while receiving.
BUSY_TX	0 x 02	The transceiver is asked to change its state while transmitting.
FORCE_TRX_OFF	0 x 03	The transceiver is to be switched off.
IDLE	0 x 04	The CCA attempt has detected an idle channel.
INVALID_PARAMETER	0 x 05	A SET/GET request was issued with a parameter in the primitive that is out of the valid range.
RX_ON	0 x 06	The transceiver is in or is to be configured into the receiver enabled state.
SUCCESS	0 x 07	A SET/GET, an ED operation, or a transceiver state change was successful.
TRX_OFF	0 x 08	The transceiver is in or is to be configured into the transceiver disabled state.
TX_ON	0 x 09	The transceiver is in or is to be configured into the transmitter enabled state.
UNSUPPORTED_ATTRIBUTE	0 x 0a	A SET/GET request was issued with the identifier of an attribute that is not supported.

6.3 PPDU format

This clause specifies the format of the PPDU packet.

For convenience, the PPDU packet structure is presented so that the leftmost field as written in this standard shall be transmitted or received first. All multiple octet fields shall be transmitted or received least significant octet first and each octet shall be transmitted or received least significant bit (LSB) first. The same transmission order should apply to data fields transferred between the PHY and MAC sublayer.

Each PPDU packet consists of the following basic components:

— A SHR, which allows a receiving device to synchronize and lock onto the bit stream.
— A PHR, which contains frame length information.
— A variable length payload, which carries the MAC sublayer frame.

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6.3.1 General packet format

The PPDU packet structure shall be formatted as illustrated in Figure 16.

Octets: 4	1	1		variable
Preamble	SFD	Frame length (7 bits)	Reserved (1 bit)	PSDU
SHR		PHR		PHY payload

Figure 16—Format of the PPDU

6.3.1.1 Preamble field

The preamble field is used by the transceiver to obtain chip and symbol synchronization with an incoming message. The preamble field shall be composed of 32 binary zeros.

6.3.1.2 SFD field

The SFD is an 8 bit field indicating the end of the synchronization (preamble) field and the start of the packet data. The SFD shall be formatted as illustrated in Figure 17.

Bits: 0	1	2	3	4	5	6	7
1	1	1	0	0	1	0	1

Figure 17—Format of the SFD field

6.3.1.3 Frame length field

The frame length field is 7 bits in length and specifies the total number of octets contained in the PSDU (i.e., PHY payload). It is a value between 0 and *aMaxPHYPacketSize* (see 6.4). Table 18 summarizes the type of payload versus the frame length value.

Table 18—Frame length values

Frame length values	Payload
0–4	Reserved
5	MPDU (Acknowledgment)
6–7	Reserved
8 to *aMaxPHYPacketSize*	MPDU

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6.3.1.4 PSDU field

The PSDU field has a variable length and carries the data of the PHY packet. For all packet types of length five octets or greater than seven octets, the PSDU contains the MAC sublayer frame (i.e., MPDU).

6.4 PHY constants and PIB attributes

This subclause specifies the constants and attributes required by the PHY.

6.4.1 PHY constants

The constants that define the characteristics of the PHY are presented in Table 19. These constants are hardware dependent and cannot be changed during operation.

Table 19—PHY constants

Constant	Description	Value
aMaxPHYPacketSize	The maximum PSDU size (in octets) the PHY shall be able to receive.	127
aTurnaroundTime	RX-to-TX or TX-to-RX maximum turnaround time (see 6.9.1 and 6.9.2)	12 symbol periods

6.4.2 PHY PIB attributes

The PHY PIB comprises the attributes required to manage the PHY of a device. Each of these attributes can be read or written using the PLME-GET.request and PLME-SET.request primitives, respectively. The attributes contained in the PHY PIB are presented in Table 20.

6.5 2450 MHz PHY specifications

The requirements for the 2450 MHz PHY are specified in 6.5.1 through 6.5.3.

6.5.1 Data rate

The data rate of the IEEE 802.15.4 (2450 MHz) PHY shall be 250 kb/s.

6.5.2 Modulation and spreading

The 2450 MHz PHY employs a 16-ary quasi-orthogonal modulation technique. During each data symbol period, four information bits are used to select one of 16 nearly orthogonal pseudo-random noise (PN) sequences to be transmitted. The PN sequences for successive data symbols are concatenated, and the aggregate chip sequence is modulated onto the carrier using offset quadrature phase-shift keying (O-QPSK).

6.5.2.1 Reference modulator diagram

The functional block diagram in Figure 18 is provided as a reference for specifying the 2450 MHz PHY modulation and spreading functions. The number in each block refers to the subclause that describes that function.

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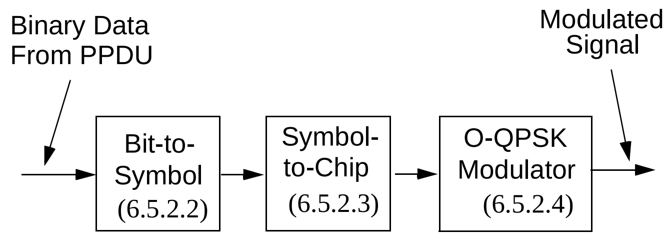

Figure 18—Modulation and spreading functions

Table 20—PHY PIB attributes

Attribute	Identifier	Type	Range	Description
phyCurrentChannel	0 x 00	Integer	0–26	The RF channel to use for all following transmissions and receptions (see 6.1.2).
phyChannelsSupported	0 x 01	Array	See description	The 5 most significant bits (MSBs) (b_{27},... , b_{31}) of *phyChannelsSupported* shall indicate the channel page supported, and the 27 LSBs (b_0, b_1, ... b_{26}) shall indicate the status (1=available, 0=unavailable) for each of the 27 valid channels (b_k shall indicate the status of channel *k* as in 6.1.2).
phyTransmitPower	0 x 02	Bitmap	0 x 00–0xbf	The 2 MSBs represent the tolerance on the transmit power: 00 = ± 1 dB 01 = ± 3 dB 10 = ± 6 dB The 6 LSBs represent a signed integer in twos-complement format, corresponding to the nominal transmit power of the device in decibels relative to 1 mW. The lowest value of *phyTransmitPower* shall be interpreted as less than or equal to –32 dBm.
phyCCAMode	0 x 03	Integer	1–3	The CCA mode (see 6.9.9).
phyCurrentPage	0 x 04	Integer	0-31	This is the current PHY page. This is used in conjunction with *phyCurrentChannel* to uniquely identify the channel currently being used.
phyPagesSupported	0 x 05	Bitmap	See description	A read only bitmap of which pages are supported by the PHY.

6.5.2.2 Bit-to-symbol mapping

All binary data contained in the PPDU shall be encoded using the modulation and spreading functions shown in Figure 18. This subclause describes how binary information is mapped into data symbols.

The 4 LSBs (b_0, b_1, b_2, b_3) of each octet shall map into one data symbol, and the 4 MSBs (b_4, b_5, b_6, b_7) of each octet shall map into the next data symbol. Each octet of the PPDU is processed through the modulation and spreading functions (see Figure 18) sequentially, beginning with the preamble field and ending with the

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last octet of the PSDU. Within each octet, the least significant symbol (b_0, b_1, b_2, b_3) is processed first and the most significant symbol (b_4, b_5, b_6, b_7) is processed second.

6.5.2.3 Symbol-to-chip mapping

Each data symbol shall be mapped into a 32-chip PN sequence as specified in Table 21. The PN sequences are related to each other through cyclic shifts and/or conjugation (i.e., inversion of odd-indexed chip values).

Table 21—Symbol-to-chip mapping

Data symbol (decimal)	Data symbol (binary) (b_0, b_1, b_2, b_3)	Chip values (c_0 c_1 ... c_{30} c_{31})
0	0 0 0 0	1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0
1	1 0 0 0	1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0
2	0 1 0 0	0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0
3	1 1 0 0	0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1
4	0 0 1 0	0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1
5	1 0 1 0	0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0
6	0 1 1 0	1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1
7	1 1 1 0	1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1
8	0 0 0 1	1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1
9	1 0 0 1	1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1
10	0 1 0 1	0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1
11	1 1 0 1	0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0
12	0 0 1 1	0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0
13	1 0 1 1	0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1
14	0 1 1 1	1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0
15	1 1 1 1	1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0

6.5.2.4 O-QPSK modulation

The chip sequences representing each data symbol are modulated onto the carrier using O-QPSK with half-sine pulse shaping. Even-indexed chips are modulated onto the in-phase (I) carrier and odd-indexed chips are modulated onto the quadrature-phase (Q) carrier. Because each data symbol is represented by a 32-chip sequence, the chip rate (nominally 2.0 Mchip/s) is 32 times the symbol rate. To form the offset between I-

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phase and Q-phase chip modulation, the Q-phase chips shall be delayed by T_c with respect to the I-phase chips (see Figure 19), where T_c is the inverse of the chip rate.

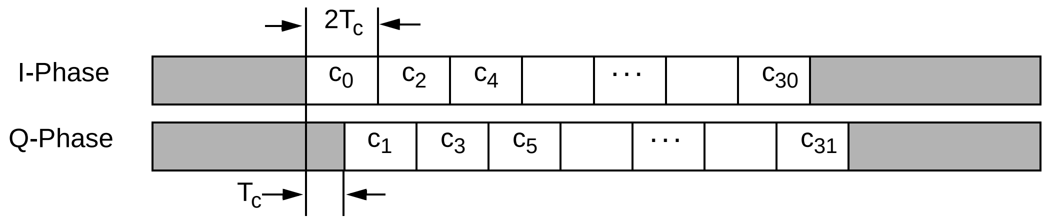

Figure 19—O-QPSK chip offsets

6.5.2.5 Pulse shape

The half-sine pulse shape used to represent each baseband chip is described by Equation (1):

$$p(t) = \begin{cases} \sin\left(\pi \frac{t}{2T_c}\right), & 0 \le t \le 2T_c \\ 0, & otherwise \end{cases} \tag{1}$$

Figure 20 shows a sample baseband chip sequence (the zero sequence) with half-sine pulse shaping.

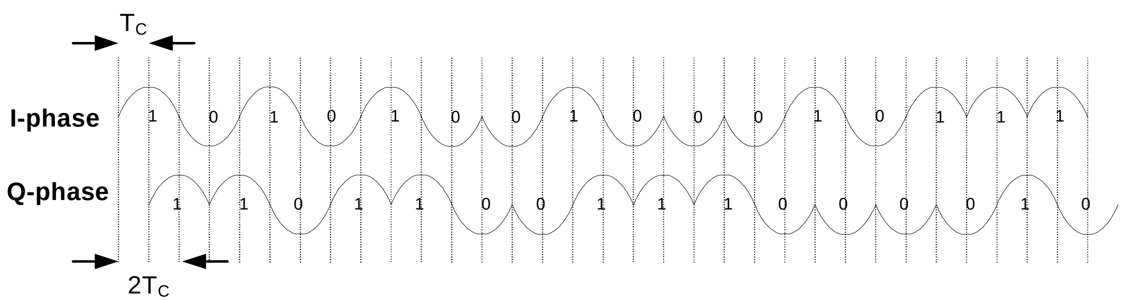

Figure 20—Sample baseband chip sequences with pulse shaping

6.5.2.6 Chip transmission order

During each symbol period the least significant chip, c_0, is transmitted first and the most significant chip, c_{31}, is transmitted last.

6.5.3 2450 MHz band radio specification

In addition to meeting regional regulatory requirements, devices operating in the 2450 MHz band shall also meet the radio requirements in 6.5.3.1 through 6.5.3.4.

6.5.3.1 Transmit power spectral density (PSD) mask

The transmitted spectral products shall be less than the limits specified in Table 22. For both relative and absolute limits, average spectral power shall be measured using a 100 kHz resolution bandwidth. For the

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relative limit, the reference level shall be the highest average spectral power measured within ± 1 MHz of the carrier frequency.

Table 22—Transmit PSD limits

Frequency	Relative limit	Absolute limit
$\lvert f - f_c \rvert > 3.5$ MHz	–20 dB	–30 dBm

6.5.3.2 Symbol rate

The 2450 MHz PHY symbol rate shall be 62.5 ksymbol/s ± 40 ppm.

6.5.3.3 Receiver sensitivity

Under the conditions specified in 6.1.6, a compliant device shall be capable of achieving a sensitivity of –85 dBm or better.

6.5.3.4 Receiver jamming resistance

The minimum jamming resistance levels are given in Table 23. The adjacent channel is one on either side of the desired channel that is closest in frequency to the desired channel, and the alternate channel is one more removed from the adjacent channel. For example, when channel 13 is the desired channel, channel 12 and channel 14 are the adjacent channels, and channel 11 and channel 15 are the alternate channels.

Table 23—Minimum receiver jamming resistance requirements for 2450 MHz PHY

Adjacent channel rejection	Alternate channel rejection
0 dB	30 dB

The adjacent channel rejection shall be measured as follows. The desired signal shall be a compliant 2450 MHz IEEE 802.15.4 signal of pseudo-random data. The desired signal is input to the receiver at a level 3 dB above the maximum allowed receiver sensitivity given in 6.5.3.3.

In either the adjacent or the alternate channel, an IEEE 802.15.4 signal is input at the relative level specified in Table 23. The test shall be performed for only one interfering signal at a time. The receiver shall meet the error rate criteria defined in 6.1.6 under these conditions.

6.6 868/915 MHz band PHY specifications

The requirements for the 868/915 MHz band PHY are specified in 6.6.1 through 6.6.3.

6.6.1 868/915 MHz band data rates

The data rate of the 868/915 MHz band PHY shall be 20 kb/s when operating in the 868 MHz band and 40 kb/s when operating in the 915 MHz band.

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6.6.2 Modulation and spreading

The 868/915 MHz PHY shall employ direct sequence spread spectrum (DSSS) with binary phase-shift keying (BPSK) used for chip modulation and differential encoding used for data symbol encoding.

6.6.2.1 Reference modulator diagram

The functional block diagram in Figure 21 is provided as a reference for specifying the 868/915 MHz band PHY modulation and spreading functions. The number in each block refers to the subclause that describes that function. Each bit in the PPDU shall be processed through the differential encoding, bit-to-chip mapping and modulation functions in octet-wise order, beginning with the preamble field and ending with the last octet of the PSDU. Within each octet, the LSB, b0, is processed first and the MSB, b7, is processed last.

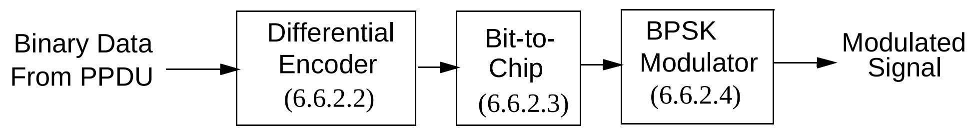

Figure 21—Modulation and spreading functions

6.6.2.2 Differential encoding

Differential encoding is the modulo-2 addition (exclusive or) of a raw data bit with the previous encoded bit. This is performed by the transmitter and can be described by Equation (2):

$$E_n = R_n \oplus E_{n-1} \quad (2)$$

where

R_n is the raw data bit being encoded,
E_n is the corresponding differentially encoded bit,
E_{n-1} is the previous differentially encoded bit.

For each packet transmitted, R_1 is the first raw data bit to be encoded and E_0 is assumed to be zero.

Conversely, the decoding process, as performed at the receiver, can be described by Equation (3):

$$R_n = E_n \oplus E_{n-1} \quad (3)$$

For each packet received, E_1 is the first bit to be decoded, and E_0 is assumed to be zero.

6.6.2.3 Bit-to-chip mapping

Each input bit shall be mapped into a 15-chip PN sequence as specified in Table 24.

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Table 24—Symbol-to-chip mapping

Input bits	Chip values (c_0 c_1 ... c_{14})
0	1 1 1 1 0 1 0 1 1 0 0 1 0 0 0
1	0 0 0 0 1 0 1 0 0 1 1 0 1 1 1

6.6.2.4 BPSK modulation

The chip sequences are modulated onto the carrier using BPSK with raised cosine pulse shaping (roll-off factor = 1). The chip rate is 300 kchip/s for the 868 MHz band and 600 kchip/s in the 915 MHz band.

6.6.2.4.1 Pulse shape

The raised cosine pulse shape (roll-off factor = 1) used to represent each baseband chip is described by Equation (4):

$$p(t) = \frac{\sin(\pi t / T_c)}{\pi t / T_c} \frac{\cos(\pi t / T_c)}{1 - (4t^2 / T_c^2)} \tag{4}$$

6.6.2.4.2 Chip transmission order

During each symbol period, the least significant chip, c_0, is transmitted first, and the most significant chip, c_{15}, is transmitted last.

6.6.3 868/915 MHz band radio specification

In addition to meeting regional regulatory requirements, devices operating in the 868/915 MHz bands shall also meet the radio requirements in 6.6.3.1 through 6.6.3.5.

6.6.3.1 Operating frequency range

The 868/915 MHz PHY operates in the 868.0–868.6 MHz frequency band and in the 902–928 MHz frequency band.

6.6.3.2 915 MHz band transmit PSD mask

The transmitted spectral products shall be less than the limits specified in Table 25. For both relative and absolute limits, average spectral power shall be measured using a 100 kHz resolution bandwidth. For the relative limit, the reference level shall be the highest average spectral power measured within ± 600 kHz of the carrier frequency.

Table 25—915 MHz band transmit PSD limits

Frequency	Relative limit	Absolute limit
$\lvert f - f_c \rvert > 1.2$ MHz	–20 dB	–20 dBm

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6.6.3.3 Symbol rate

The IEEE 802.15.4 PHY symbol rate shall be 20 ksymbol/s when operating in the 868 MHz band and 40 ksymbol/s when operating in the 915 MHz band with an accuracy of ± 40 ppm.

6.6.3.4 Receiver sensitivity

Under the conditions specified in 6.1.6, a compliant device shall be capable of achieving a sensitivity of –92 dBm or better.

6.6.3.5 Receiver jamming resistance

This subclause applies only to the 902–928 MHz band as there is only one channel available in the 868.0–868.6 MHz band.

The minimum jamming resistance levels are given in Table 26. The adjacent channel is one on either side of the desired channel that is closest in frequency to the desired channel, and the alternate channel is one more removed from the adjacent channel. For example, when channel 5 is the desired channel, channel 4 and channel 6 are the adjacent channels and channel 3 and channel 7 are the alternate channels.

Table 26—Minimum receiver jamming resistance requirements for 915 MHz PHY

Adjacent channel rejection	Alternate channel rejection
0 dB	30 dB

The adjacent channel rejection shall be measured as follows: The desired signal shall be a compliant 915 MHz IEEE 802.15.4 signal, as defined by 6.6, of pseudo-random data. The desired signal is input to the receiver at a level 3 dB above the maximum allowed receiver sensitivity given in 6.6.3.4.

In either the adjacent or the alternate channel, a compliant IEEE 802.15.4 signal, as defined by 6.6, is input at the relative level specified in Table 26. The test shall be performed for only one interfering signal at a time. The receiver shall meet the error rate criteria defined in 6.1.6 under these conditions.

6.7 868/915 MHz band enhanced PSSS alternate PHY specifications

The requirements for the 868/915 MHz band enhanced PSSS PHY are specified in 6.7.1 through 6.7.4.

6.7.1 868/915 MHz band data rates

The data rate of the IEEE 802.15.4b enhanced PSSS PHY shall be 206 kbit/s when operating in the 868 MHz band and 250 kbit/s when operating in the 915 MHz band.

6.7.2 Modulation and spreading

The enhanced PSSS PHY employs a (31+1)-ary quasi-orthogonal, parallel modulation technique. During each data symbol period, 15 information bits are used to each select one of 15 for 868 MHz and 5 information bits are used to each select one of 5 for 915 MHz nearly orthogonal pseudo-random (PN) sequences or their inverses. This results in 15 for 868 MHz and 5 for 915 MHz PN sequences being superpositioned, a simple precoding is then executed per symbol, and the aggregate (31+1)-chip sequence is modulated onto the carrier using amplitude shift keying (ASK).

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6.7.2.1 Reference modulator diagram

The functional block diagram in Figure 22 is provided as a reference for specifying the enhanced PSSS PHY modulation and spreading functions. The number in each block refers to the subclause that describes that function.

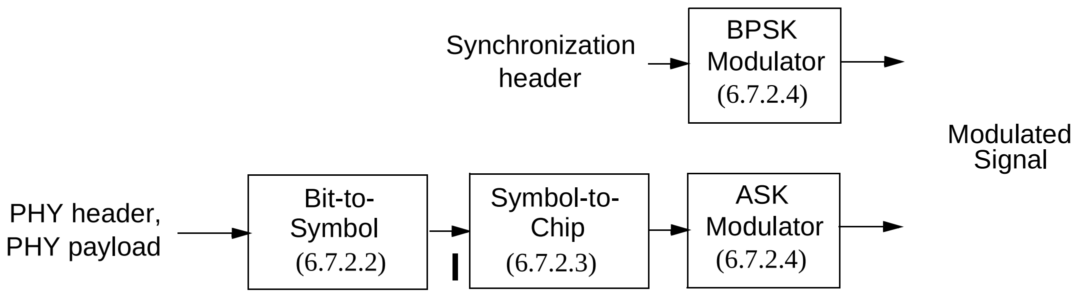

Figure 22—Modulation and spreading functions

Each octet of the PPDU is sequentially processed through the spreading and modulation functions (see Figure 22). The synchronization header shall be encoded using the BPSK modulator and the PHY header and PHY payload shall be processed using the Bit-to-Symbol, Symbol-to-Chip spreading and the ASK modulator as shown in Figure 22.

Before the transmission of the first data octet of the PHY header, a synchronization header with a preamble and a start of frame delimiter shall be transmitted as described in 6.7.4.

6.7.2.2 Bit-to-symbol mapping

This subclause describes how binary information is mapped into data symbols.

The first 15 bits for 868 MHz and the first 5 bits for 915 MHz starting at the PHY header - starting with the least significant bit (b0) of the first octet of the PHY header and continuing with the subsequent octet of the PHY header - shall be mapped into the first data symbol. Further 15 bits for 868 MHz and further 5 bits for 915 MHz continuing until the end of the PPDU shall be mapped sequentially to each subsequent data symbol until all octets of the PHY header and PHY payload have been mapped into symbols, always mapping the least significant bits of any octet first. For each symbol the least significant chip shall be the first chip transmitted over the air. The last input bits shall be followed by padding, with "0" bits, of its high order bits to fill out the symbol.

6.7.2.3 Symbol-to-chip mapping

Each data symbol shall be mapped into a 32-chip sequence as described in this subclause.

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Figure 23 provides an overview of the symbol-to-chip mapping.

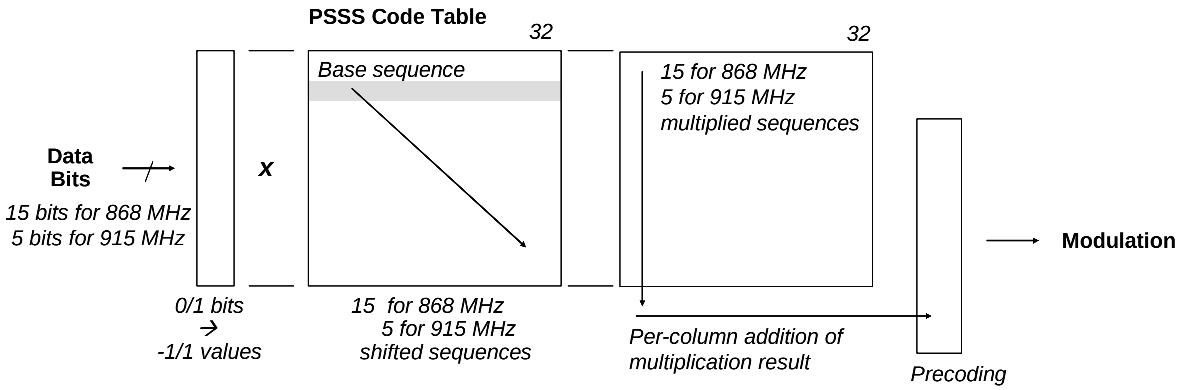

Figure 23—Symbol-to-Chip mapping for PHY header and PHY payload

Each bit of the data stream is multiplied with its corresponding sequence of the code table defined in Table 27 for 868 MHz and Table 28 for 915 MHz. The PSSS code table was generated by selecting 15 for 868 MHz and 5 for 915 MHz cyclically shifted sequences of a 31-chip base sequence and then adding a one bit cyclic extension to each sequence.

Table 27—PSSS Code table used in Symbol-to-Chip mapping for 868 MHz

Sequence number	Chip number																														
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1
1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1
2	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1
3	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1
4	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1
5	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1
6	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1
7	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1
8	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1
9	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1
10	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1
11	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1
12	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1
13	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1
14	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1

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Table 28—PSSS Code table used in Symbol-to-Chip mapping for 915MHz

Sequence number	Chip number																															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1
1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1
2	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1
3	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1	-1	1	1	-1	-1	1
4	1	-1	1	1	-1	-1	1	1	1	1	1	-1	-1	-1	1	1	-1	1	1	1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	1

The vector of bits in the data stream is multiplied with the PSSS code table. i.e. bit b0 of the data stream is multiplied with sequence number "0", bit b1 of the data stream with sequence number "1", etc. For the value "0" of the bits of the data stream the corresponding sequence is multiplied with "-1", for the value "1" and multiplied with "1", for the value "1". The result is a table formed - depending on the bit values of the data stream - row-by-row with the actual or inverse of the corresponding PSSS code sequence.

Subsequently, the chips of each multiplied sequence are added per column, e.g. the chips number "3" of each multiplied sequence are added to form the chip c3. The per-column results are 32 chips c0…c31.

After the per-column addition, precoding is executed for the 32 chips of each symbol. Precoding is performed in two steps: In the first step the values of the sequence of the 32 multi-valued chips are aligned symmetrical to zero without changing the relative difference between the chips. In the second step, the values of all 32 multi-valued chips in the symbol shall be scaled linearly so that the signal output to the antenna satisfies the specified error measurement criteria in 6.9.3.1. The precoding of one symbol is executed independent of the precoding of any other symbol with the two steps described in Equation (5) and Equation (6) as follows:

$$p'(m) = p(m) - \frac{(Max + Min)}{2} \tag{5}$$

where *p(m)* is the current PSSS symbol and *p'(m)* is the aligned symmetric to zero PSSS symbol and *Max* and *Min* are the maximum and minimum chip amplitudes within the symbol respectively and

$$p''(m) = \frac{p'(m)}{Max'} \tag{6}$$

where *Max'* is the maximum chip amplitude within the aligned symmetric to zero PSSS symbol *p'(m)*.

The precoded sequence of 32 multi-value chips is modulated as described in 6.7.2.4.

6.7.2.4 ASK modulation

The chip sequences representing each data symbol are modulated onto the carrier using ASK with square root raised cosine pulse shaping. The chip rate is 440 kchips/s for 868 MHz and 1600 kchips/s for 915 MHz.

6.7.2.4.1 Pulse shape

The pulse shape used to represent each baseband chip is described by Equation (7):

$$p(t) = 4r\frac{\cos((1+r)\pi t/T_c) + (\sin((1-r)\pi t/T_c))/(4rt/T_c)}{\pi\sqrt{T_c}((4rt/T_c)^2 - 1)} \tag{7}$$

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with a rolloff factor r = 0.1 for 868 MHz and r = 0.2 for 915 MHz.

6.7.2.4.2 Chip transmission order

During each symbol period, the least significant chip, c_0, is transmitted first, and the most significant chip, c_{31}, is transmitted last.

6.7.3 868/915 MHz band radio specification for the enhanced PSSS PHY

In addition to meeting regional regulatory requirements, devices operating in the 868/915 MHz bands shall also meet the radio requirements in 6.7.3.1 through 6.7.3.5.

6.7.3.1 Operating frequency range

The 868/915 MHz enhanced PSSS PHY operates in the 868.0–868.6 MHz frequency band and in the 902–928 MHz frequency band.

6.7.3.2 915 MHz band transmit PSD mask

The transmitted spectral products shall be less than the limits specified in Table 29. For both relative and absolute limits, average spectral power shall be measured using a 100 kHz resolution bandwidth. For the relative limit, the reference level shall be the highest average spectral power measured within ± 600 kHz of the carrier frequency.

Table 29—915 MHz band enhanced PSSS PHY transmit PSD limits

Frequency	Relative limit	Absolute limit
$\|f - f_c\| > 1.2$ MHz	–20 dB	–20 dBm

6.7.3.3 Symbol rate

The enhanced PSSS PHY symbol rate shall be 13.75 ksymbols/s ± 40 ppm for 868 MHz and 62.5 ksymbols/s ± 40 ppm for 915 MHz.

6.7.3.4 Receiver sensitivity

Under the conditions specified in 6.1.6, a compliant device shall be capable of achieving a sensitivity of -92 dBm or better.

6.7.3.5 Receiver jamming resistance

This subclause applies only to the 902–928 MHz band as there is only one channel available in the 868.0–868.6 MHz band.

The minimum jamming resistance levels are given in Table 30. The adjacent channel is one on either side of the desired channel that is closest in frequency to the desired channel, and the alternate channel is one more removed from the adjacent channel. For example, when channel 5 is the desired channel, channel 4 and channel 6 are the adjacent channels and channel 3 and channel 7 are the alternate channels.

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Table 30—Minimum receiver jamming resistance requirements for 915 MHz enhanced PSSS PHY

Adjacent channel rejection	Alternate channel rejection
0 dB	30 dB

The adjacent channel rejection shall be measured as follows: The desired signal shall be a compliant 915 MHz IEEE 802.15.4 signal, as defined by 6.7, of pseudo-random data. The desired signal is input to the receiver at a level 3 dB above the maximum allowed receiver sensitivity given in 6.7.3.4.

In either the adjacent or the alternate channel, a compliant IEEE 802.15.4 signal, as defined by 6.7, is input at the relative level specified in Table 30. The test shall be performed for only one interfering signal at a time. The receiver shall meet the error rate criteria defined in 6.1.6 under these conditions.

6.7.4 Synchronization header for enhanced PSSS PHY

Before the transmission of the first data octet of the PDU, a synchronization header with a preamble and a start of frame delimiter shall be transmitted.

The entire synchronization header and frame delimiter are transmitted with BPSK modulation with raised cosine pulse shaping as defined in 6.7.2.4.1 at the same chip rate as the chips transmitted for the PPDU data. Figure 16 illustrates the synchronization header.

6.7.4.1 Preamble for enhanced PSSS PHY

The preamble is generated by repeating a 26-chip sequence 8 times. The 26-chip sequence is formed from a length 13 Barker code followed by its inverse as shown in Table 31. The left-most chip number "0" in the diagram is transmitted first.

Table 31—26-Chip sequence used in generatring preanble for enhanced PSSS PHY

Chip number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Value	0	0	0	0	1	1	0	0	1	0	1	0	0	1	1	1	1	0	0	1	1	0	1	0	1	1
	Barker Sequence													Barker Sequence Inverted												

6.7.4.2 Start-of-frame delimiter for enhanced PSSS PHY

The SFD is an 8 bit field indicating the end of the synchronization (preamble) field and the start of the packet data. The SFD shall be formatted as illustrated in Table 18.

6.8 868/915 MHz band enhanced O-QPSK alternate PHY specifications

The requirements for the 868/915 MHz band enhanced O-QPSK PHY are specified in 6.8.1 through 6.8.3.

6.8.1 868/915 MHz band data rates

The data rate of the IEEE 802.15.4b enhanced O-QPSK PHY shall be 100 kbit/s when operating in the 868 MHz band and 250 kbit/s when operating in the 915 MHz band.

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6.8.2 Modulation and spreading

The enhanced O-QPSK PHY employs a 16-ary quasi-orthogonal modulation technique. During each data symbol period, four information bits are used to select one of 16 nearly orthogonal pseudo-random noise (PN) sequences to be transmitted. The PN sequences for successive data symbols are concatenated, and the aggregate chip sequence is modulated onto the carrier using offset quadrature phase-shift keying (O-QPSK).

6.8.2.1 Reference modulator diagram

The functional block diagram in Figure 21 is provided as a reference for specifying the 868/915 MHz band PHY modulation and spreading functions. The number in each block refers to the subclause that describes that function. Each bit in the PPDU shall be processed through the differential encoding, bit-to-chip mapping and modulation functions in octet-wise order, beginning with the preamble field and ending with the last octet of the PSDU. Within each octet, the LSB, b0, is processed first and the MSB, b7, is processed last.

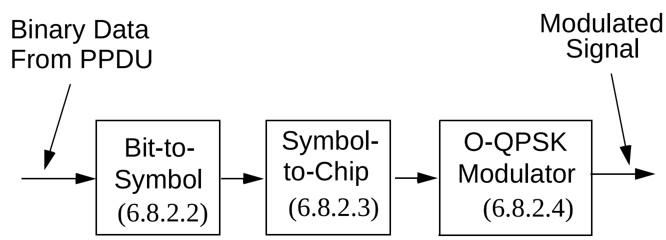

Figure 24—Modulation and spreading functions

6.8.2.2 Bit-to-symbol maping

All binary data contained in the PPDU shall be encoded using the modulation and spreading functions shown in Figure 24. This subclause describes how binary information is mapped into data symbols.

The 4 LSBs (b0, b1, b2, b3) of each octet shall map into one data symbol, and the 4 MSBs (b4, b5, b6, b7) of each octet shall map into the next data symbol. Each octet of the PPDU is processed through the modulation and spreading functions (see Figure 24) sequentially, beginning with the preamble field and ending with the last octet of the PSDU. Within each octet, the least significant symbol (b0, b1, b2, b3) is processed first and the most significant symbol (b4, b5, b6, b7) is processed second.

6.8.2.3 Symbol-to-chip mapping

Each data symbol shall be mapped into a 16-chip PN sequence as specified in Table 31.

Table 32—Symbol-to-chip mapping for enhanced O-QPSK

Data symbol (decimal)	Data symbol (binary) (b_0, b_1, b_2, b_3)	Chip values (c_0 c_1 ... c_{14} c_{15})
0	0 0 0 0	0 0 1 1 1 1 1 0 0 0 1 0 0 1 0 1
1	1 0 0 0	0 1 0 0 1 1 1 1 1 0 0 0 1 0 0 1
2	0 1 0 0	0 1 0 1 0 0 1 1 1 1 1 0 0 0 1 0
3	1 1 0 0	1 0 0 1 0 1 0 0 1 1 1 1 1 0 0 0

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Table 32—Symbol-to-chip mapping for enhanced O-QPSK *(continued)*

Data symbol (decimal)	Data symbol (binary) (b_0, b_1, b_2, b_3)	Chip values (c_0 c_1 ... c_{14} c_{15})
4	0 0 1 0	0 0 1 0 0 1 0 1 0 0 1 1 1 1 1 0
5	1 0 1 0	1 0 0 0 1 0 0 1 0 1 0 0 1 1 1 1
6	0 1 1 0	1 1 1 0 0 0 1 0 0 1 0 1 0 0 1 1
7	1 1 1 0	1 1 1 1 1 0 0 0 1 0 0 1 0 1 0 0
8	0 0 0 1	0 1 1 0 1 0 1 1 0 1 1 1 0 0 0 0
9	1 0 0 1	0 0 0 1 1 0 1 0 1 1 0 1 1 1 0 0
10	0 1 0 1	0 0 0 0 0 1 1 0 1 0 1 1 0 1 1 1
11	1 1 0 1	1 1 0 0 0 0 0 1 1 0 1 0 1 1 0 1
12	0 0 1 1	0 1 1 1 0 0 0 0 0 1 1 0 1 0 1 1
13	1 0 1 1	1 1 0 1 1 1 0 0 0 0 0 1 1 0 1 0
14	0 1 1 1	1 0 1 1 0 1 1 1 0 0 0 0 0 1 1 0
15	1 1 1 1	1 0 1 0 1 1 0 1 1 1 0 0 0 0 0 1

6.8.2.4 O-QPSK modulation

The chip sequences representing each data symbol are modulated onto the carrier using O-QPSK with half-sine pulse shaping. Even-indexed chips are modulated onto the in-phase (I) carrier and odd-indexed chips are modulated onto the quadrature-phase (Q) carrier. Because each data symbol is represented by a 16-chip sequence, the chip rate (nominally 400 Kchip/s and 1.0 Mchip/s for the 868 MHz and 915 MHz bands respectively) is 16 times the symbol rate. To form the offset between I-phase and Q-phase chip modulation, the Q-phase chips shall be delayed by T_c with respect to the I-phase chips (see Figure 25), where T_c is the inverse of the chip rate.

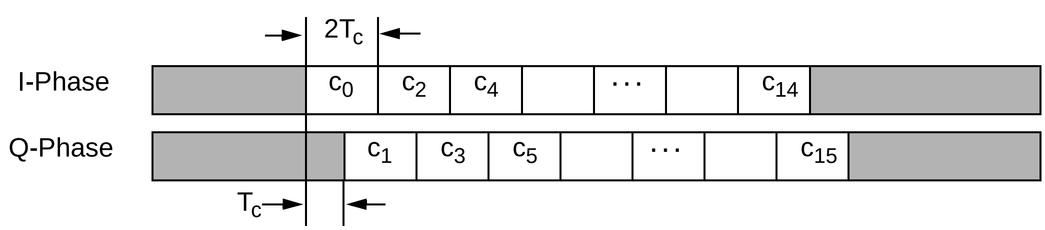

Figure 25—O-QPSK chip offsets

6.8.2.5 Pulse shape

The half-sine pulse shape used to represent each baseband chip is described by Equation (8):

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$$p(t) = \begin{cases} \sin\left(\pi\frac{t}{2T_c}\right), & 0 \le t \le 2T_c \\ 0, & otherwise \end{cases} \tag{8}$$

Figure 26 shows a sample baseband chip sequence (the zero sequence) with half-sine pulse shaping.

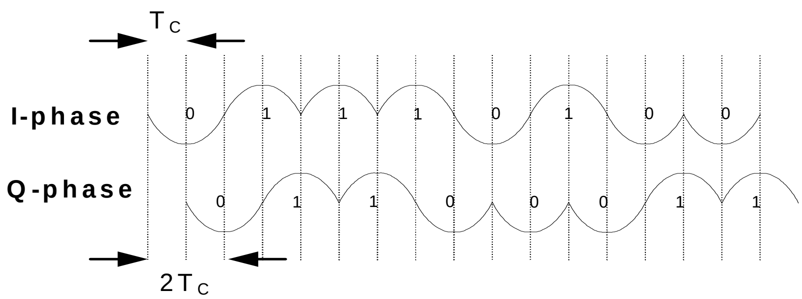

Figure 26—Sample baseband chip sequences with pulse shaping

6.8.2.6 Chip transmission order

During each symbol period, the least significant chip, c_0, is transmitted first, and the most significant chip, c_{15}, is transmitted last.

6.8.3 868/915 MHz band radio specification

In addition to meeting regional regulatory requirements, devices operating in the 868/915 MHz bands shall also meet the radio requirements in 6.8.3.1 through 6.8.3.5.

6.8.3.1 Operating frequency range

The 868/915 MHz enhanced O-QPSK PHY operates in the 868.0–868.6 MHz frequency band and in the 902–928 MHz frequency band.

6.8.3.2 Transmit PSD mask

When operating in the 868 MHz band, the signal shall be filtered before transmission to regulate the transmit PSD. A raised cosine filter with roll-off factor r = 0.6 shall be used, which is specified in Equation (9) by:

$$p(t) = \frac{\sin(\pi t/T_c)}{\pi t/T_c}\frac{\cos(r\pi t/T_c)}{1-4r^2t^2/T_c^2} \tag{9}$$

When operating in the 915 MHz band, the transmitted spectral products shall be less than the limits specified in Table 33. For both relative and absolute limits, average spectral power shall be measured using a 100 kHz resolution bandwidth. For the relative limit, the reference level shall be the highest average spectral power measured within ± 1 MHz of the carrier frequency fc.

Table 33—915 MHz band enhanced O-QPSK PHY transmit PSD limits

Frequency	Relative limit	Absolute limit
$\lvert f - f_c \rvert > 1.2$ MHz	–20 dB	–20 dBm

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6.8.3.3 Symbol rate

The IEEE 802.15.4b enhanced O-QPSK PHY symbol rate shall be 25 ksymbol/s when operating in the 868 MHz band and 62.5 ksymbol/s when operating in the 915 MHz band with an accuracy of ± 40 ppm.

6.8.3.4 Receiver sensitivity

Under the conditions specified in 6.1.6, a compliant device shall be capable of achieving a sensitivity of –90 dBm or better.

6.8.3.5 Receiver jamming resistance

This subclause applies only to the 902–928 MHz band as there is only one channel available in the 868.0–868.6 MHz band.

The minimum jamming resistance levels are given in Table 34. The adjacent channel is one on either side of the desired channel that is closest in frequency to the desired channel, and the alternate channel is one more removed from the adjacent channel. For example, when channel 5 is the desired channel, channel 4 and channel 6 are the adjacent channels and channel 3 and channel 7 are the alternate channels.

Table 34—Mnimum receiver jamming resistance requirements for 915 MHz enhanced O-QPSK PHY

Adjacent channel rejection	Alternate channel rejection
0 dB	30 dB

The adjacent channel rejection shall be measured as follows: The desired signal shall be a compliant 915 MHz IEEE 802.15.4 signal, as defined by 6.8, of pseudo-random data. The desired signal is input to the receiver at a level 3 dB above the maximum allowed receiver sensitivity given in 6.8.3.4.

In either the adjacent or the alternate channel, a compliant IEEE 802.15.4 signal, as defined by 6.8, is input at the relative level specified in Table 34. The test shall be performed for only one interfering signal at a time. The receiver shall meet the error rate criteria defined in 6.1.6 under these conditions.

6.9 General radio specifications

The specifications in 6.9.1 through 6.9.9 apply to either or both the 2450 MHz PHY and the 868/915 MHz PHY.

6.9.1 TX-to-RX turnaround time

The TX-to-RX turnaround time shall be less than *aTurnaroundTime* (see 6.4.1).

The TX-to-RX turnaround time shall be measured at the air interface from the trailing edge of the last transmitted symbol until the receiver is ready to begin the reception of the next PHY packet.

6.9.2 RX-to-TX turnaround time

The RX-to-TX turnaround time shall be less than *aTurnaroundTime* (see 6.4.1).

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The RX-to-TX turnaround time shall be measured at the air interface from the trailing edge of the last chip (of the last symbol) of a received packet until the transmitter is ready to begin transmission of the resulting acknowledgment. Actual transmission start times are specified by the MAC sublayer (see 7.5.6.4.2).

6.9.3 Error-vector magnitude (EVM) definition

The modulation accuracy of an IEEE 802.15.4 transmitter is determined with an EVM measurement. In order to calculate the EVM measurement, a time record of N received complex chip values $(\tilde{I}_j, \tilde{Q}_j)$ is captured. For each received complex chip, a decision is made about which complex chip value was transmitted. The ideal position of the chosen complex chip (the center of the decision box) is represented by the vector (I_j, Q_j). The error vector $(\delta I_j, \delta Q_j)$ is defined as the distance from this ideal position to the actual position of the received point (see Figure 27).

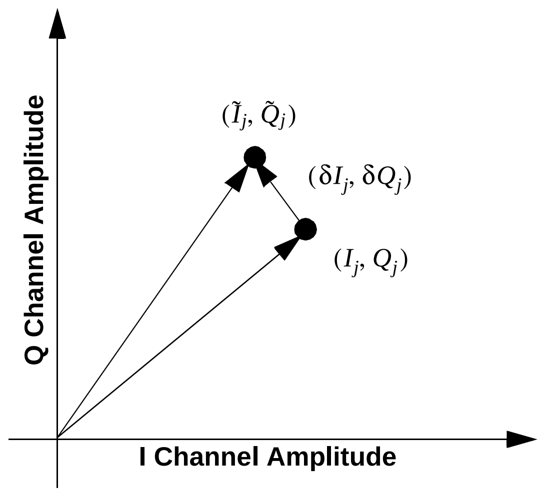

Figure 27—Error vector calculation

Thus, the received vector is the sum of the ideal vector and the error vector.

$$(\tilde{I}_j, \tilde{Q}_j) = (I_j, Q_j) + (\delta I_j, \delta Q_j) \tag{10}$$

The EVM for IEEE Std 802.15.4-2003 is defined as

$$EVM \equiv \sqrt{\frac{\frac{1}{N}\sum_{j=1}^{N}(\delta I_j^2 + \delta Q_j^2)}{S^2}} \times 100\% \tag{11}$$

where

S	is the magnitude of the vector to the ideal constellation point,
$(\delta I_j, \delta Q_j)$	is the error vector.

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6.9.3.1 EVM calculated values

An IEEE 802.15.4 transmitter shall have EVM values of less than 35% when measured for 1000 chips. The error-vector measurement shall be made on baseband I and Q chips after recovery through a reference receiver system. The reference receiver shall perform carrier lock, symbol timing recovery, and amplitude adjustment while making the measurements.

6.9.4 Transmit center frequency tolerance

The transmitted center frequency tolerance shall be ± 40 ppm maximum.

6.9.5 Transmit power

An IEEE 802.15.4 transmitter shall be capable of transmitting at least –3 dBm. Devices should transmit lower power when possible in order to reduce interference to other devices and systems.

The maximum transmit power is limited by local regulatory bodies.

6.9.6 Receiver maximum input level of desired signal

The receiver maximum input level is the maximum power level of the desired signal, in decibels relative to 1 mW, present at the input of the receiver for which the error rate criterion in 6.1.6 is met. An IEEE 802.15.4 receiver shall have a receiver maximum input level greater than or equal to –20 dBm.

6.9.7 Receiver ED

The receiver ED measurement is intended for use by a network layer as part of a channel selection algorithm. It is an estimate of the received signal power within the bandwidth of an IEEE 802.15.4 channel. No attempt is made to identify or decode signals on the channel. The ED time shall be equal to 8 symbol periods.

The ED result shall be reported to the MLME using PLME-ED.confirm (see 6.2.2.4) as an 8 bit integer ranging from 0x00 to 0xff. The minimum ED value (0) shall indicate received power less than 10 dB above the specified receiver sensitivity (see 6.5.3.3 and 6.6.3.4), and the range of received power spanned by the ED values shall be at least 40 dB. Within this range, the mapping from the received power in decibels to ED value shall be linear with an accuracy of ± 6 dB.

6.9.8 LQI

The LQI measurement is a characterization of the strength and/or quality of a received packet. The measurement may be implemented using receiver ED, a signal-to-noise ratio estimation, or a combination of these methods. The use of the LQI result by the network or application layers is not specified in this standard.

The LQI measurement shall be performed for each received packet, and the result shall be reported to the MAC sublayer using PD-DATA.indication (see 6.2.1.3) as an integer ranging from 0x00 to 0xff. The minimum and maximum LQI values (0x00 and 0xff) should be associated with the lowest and highest quality IEEE 802.15.4 signals detectable by the receiver, and LQ values in between should be uniformly distributed between these two limits. At least eight unique values of LQ shall be used.

6.9.9 CCA

The IEEE 802.15.4 PHY shall provide the capability to perform CCA according to at least one of the following three methods:

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— CCA Mode 1: Energy above threshold. CCA shall report a busy medium upon detecting any energy above the ED threshold.
— CCA Mode 2: Carrier sense only. CCA shall report a busy medium only upon the detection of a signal with the modulation and spreading characteristics of IEEE 802.15.4. This signal may be above or below the ED threshold.
— CCA Mode 3: Carrier sense with energy above threshold. CCA shall report a busy medium using a logical combination of (i) detection of a signal with the modulation and spreading characteristics of IEEE 802.15.4 and (ii) energy above the ED threshold, where the logical operator may be AND or OR.

For any of the CCA modes, if the PLME-CCA.request primitive (see 6.2.2.1) is received by the PHY during reception of a PPDU, CCA shall report a busy medium. PPDU reception is considered to be in progress following detection of the SFD, and it remains in progress until the number of octets specified by the decoded PHR has been received.

A busy channel shall be indicated by the PLME-CCA.confirm primitive (6.2.2.2) with a status of BUSY.

A clear channel shall be indicated by the PLME-CCA.confirm primitive (6.2.2.2) with a status of IDLE.

The PHY PIB attribute *phyCCAMode* (see 6.4) shall indicate the appropriate operation mode. The CCA parameters are subject to the following criteria:

a) The ED threshold shall correspond to a received signal power of at most 10 dB above the specifed receiver sensitivity (see 6.5.3.3 and 6.6.3.4).
b) The CCA detection time shall be equal to 8 symbol periods.

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