IEEE P802.15

Wireless Personal Area Networks

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Re:	
Abstract	This document combines the work done thus far by TG4p.
Purpose	This document is the first step in preparing a draft for letter ballot.
Notice	This document has been prepared to assist the IEEE P802.15. It is offered as a basis for discussion and is not binding on the contributing individual(s) or organization(s). The material in this document is subject to change in form and content after further study. The contributor(s) reserve(s) the right to add, amend or withdraw material contained herein.
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IEEE Standard for Local and metropolitan area networks—

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

Amendment X: Positive Train Control (PTC) System Physical Layer

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

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

2. Normative references

Insert the following new reference alphabetically into Clause 2:

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

3. Definitions, acronyms, and abbreviations

3.1 Definitions

Change the following definition as indicated:

BT: ~~s~~Shaping parameter for filtered FSK or GMSK modulation, where *B* is the 3 dB bandwidth of the shaping filter, and *T* is the FSK or GMSK symbol period.

Insert the following definition alphabetically into 3.1:

positive train control (PTC): A system of functional requirements for monitoring and controlling train movements to provide increased safety defined by federal law in 49 CFR 236.1005.(a).

3.2 Acronyms and abbreviations

Insert the following acronyms alphabetically into 3.2:

C4FM	continuous four-level frequency modulation
DPSK	differential phase-shift keying
GMSK	Gaussian-filtered minimum shift keying
Pi/4 DQPSK	Pi/4 differential quadrature phase-shift keying
PTC	positive train control
QPSK	quadrature phase-shift keying
RCC	rail communications and control

4. General description

Insert the following new subclause (4.1b) after 4.1a:

4.1b Introduction to positive train control (PTC)

PTC refers to a system that meets the functional performance requirements for monitoring and controlling train movements to provide increased safety as defined by federal law in 49 CFR 236.1005.(a).

PTC systems are integrated command, control, communications, and information systems for controlling train movements with safety, security, precision, and efficiency. PTC systems will improve railroad safety by significantly reducing the probability of collisions between trains, casualties to roadway workers and damage to their equipment, and over speed accidents. The National Transportation Safety Board has named PTC as one of its “most-wanted” initiatives for national transportation safety.

PTC systems are comprised of digital data link communications networks, continuous and accurate positioning systems such as National Differential GPS, on-board computers with digitized maps on locomotives and maintenance-of-way equipment, in-cab displays, throttle-brake interfaces on locomotives, wayside interface units at switches and wayside detectors, and control center computers and displays. PTC systems may also interface with tactical and strategic traffic planners, work order reporting systems, and locomotive health reporting systems. PTC systems issue movement authorities to train and maintenance-of-way crews, track the location of the trains and maintenance-of-way vehicles, have the ability to automatically enforce movement authorities, and continually update operating data systems with information on the location of trains, locomotives, cars, and crews. The remote intervention capability of PTC will permit the control center to stop a train should the locomotive crew be incapacitated. In addition to providing a greater level of safety and security, PTC systems also enable a railroad to run scheduled operations and provide improved running time, greater running time reliability, higher asset utilization, and greater track capacity. They will assist railroads in measuring and managing costs and in improving energy efficiency.

The United States Congress enacted a law called the Rail Safety Improvement Act of 2008, in order to improve rail safety. The law mandates the use of PTC for most rail and rail transit entities. PTC has four primary components:

- Equipment deployed on the locomotive/train
- Equipment deployed trackside
- Network access points deployed at or near trackside that are connected to systems operating at a remotely located control center
- A bi-directional wireless data link that connects all these elements

In the United States, there has been a plurality of wireless communication methods used since the 1970s for rail and rail transit data communications. However, while the need for mobile wireless data communications has continued to expand, there had been little effort, until now, to establish a broadly applicable open standard. This standard provides a simple, low-data rate, wireless data packet protocol suitable for machine-to-machine applications, such as PTC.

A number of radio frequency bands currently used or planned for rail and rail transit communications are included in this standard. Also included are modulation modes and error-correction techniques that enhance functionality for low-data rate vehicular communications.

5. MAC protocol

5.1 MAC functional description

5.1.1 Channel access

5.1.1.6 LLDN Superframe structure

Insert the following new subclause (5.1.1.6.7) following 5.1.1.6.6:

5.1.1.6.7 LLDN usage by an RCC device

An RCC device should support LLDN mode with an additional shared group time slot allocated for broadcasting messages from one device to all devices within range, using the slotted contention-based access method specified in 5.1.1.4.4.

If any device loses timing synchronization with the coordinator, that device will implement the CSMA mode described in 5.1.1.4, in order to allow the broadcast messages to be received.

An RCC device running in LLDN mode should always use enhanced beacon frames, in order to allow different modulation schemes to be assigned to different slot owners.

The modulation scheme of the enhanced beacon frame and the management time slots should be set by a higher layer.

The RCC Capabilities information element (IE) advertises all frequency bands, modulation schemes, and data rates supported by the coordinator, as described in 5.2.4.28a.

Devices may optionally request to use any modulation scheme advertised by the coordinator in the enhanced beacon frame.

5.1.8 Ranging

Insert the following paragraph <Editor’s note: exact placement of this text is TBD>

An RCC device should support the Ranging request IE and the Ranging response IE, as specified in 5.2.4.34. <Editor’s note: if we want to use these IEs being introduced by TG4m, then we should add them to our document for now. Because 4m is not published, the content is not available to most people unless we add it in here. We should do this before letter ballot.>

Insert the following paragraph <Editor’s note: exact placement of this text is TBD>

The PIB attribute *macEnhAckWaitDuration* should be set based on the ranging results using the formula:

$$macEnhAckWaitDuration = aUnitBackoffPeriod + aTurnaroundTime + phySHRDuration + \text{ceiling}(6 \times phySymbolsPerOctet) + 2 \times \left(\frac{d}{3 \times 10^8 \times 10^6}\right)$$

where d is the estimated range in meters.

5.1.11 LE transmission, reception and acknowledgment

5.1.11.1 Coordinated sampled listening (CSL)

5.1.11.1.4 Unicast transmission

Change step f) in paragraph three as indicated:

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

5.2 MAC frame formats

5.2.4 Information Element

5.2.4.28a RCC Capabilities IE

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

Octets: 2	2	2
PHY Frequency Bands Supported	RCC PHY Modulation Supported	DSSS DPSK Modulation Supported Feature

Figure 48aae —Format of the RCC Capabilities IE

Table 4wa contains the RCC Frequency Bands Supported field encoding, Table 4wb contains the RCC PHY Modulation Supported field encoding, and table contains the DSSS DPSK Modulation Supported Feature field encoding.

Table 4wa—RCC PHY Frequency Bands Supported field encoding

Bit number	Description
0	Band 161 MHz supported
1	Band 216 MHz supported
2	Band 217 MHz supported
3	Band 220 MHz supported
4	Band 450 MHz supported
5	Band 770 MHz supported
6	Band 800 MHz supported
7	Band 806 MHz supported
8	Band 896 MHz supported

Table 4wa—RCC PHY Frequency Bands Supported field encoding

Bit number	Description
9	Band 901 MHz supported
10	Band 915 MHz supported
11	Band 928 MHz supported
12	Band 4965 MHz supported
13	Band 5300 MHz supported
14	Band 5600 MHz supported
15	Band 5800 MHz supported

Table 4wb—RCC PHY Modulation Supported field encoding

Bit number	Description
0	GMSK 9.6 kbps supported
1	GMSK 19.2 kbps supported
2	C4FM 9.6 kbps supported
3	C4FM 19.2 kbps supported
4	C4FM 38.4 kbps supported
5	QPSK 16 kbps supported
6	QPSK 32 kbps supported
7	Pi/4 DQPSK 16 kbps supported
8	Pi/4 DQPSK 32 kbps supported
9	Pi/4 DQPSK 36 kbps supported
10	DSSS DPSK supported
11–15	Reserved

Table 4wc—RCC PHY DSSS DPSK Modulation Supported Feature field encoding

Bit number	Description
0	300 kcps chip rate supported
1	600 kcps chip rate supported
2	800 kcps chip rate supported
3	1 Mcps chip rate supported
4	1.6 Mcps chip rate supported
5	2 Mcps chip rate supported
6	3 Mcps chip rate supported

Table 4wc—RCC PHY DSSS DPSK Modulation Supported Feature field encoding

Bit number	Description
7	4 Mcps chip rate supported
8	11-chip spreading sequence supported
9	15-chip spreading sequence supported
10	20-chip spreading sequence supported
11	40-chip spreading sequence supported
12	DSSS DBPSK supported
13	DSSS DQPSK supported
14–15	Reserved

5.2.4.29 Operating Mode Description IEs

5.2.4.29.3 RCC PHY Operating Mode Description IE

The RCC PHY Operating Mode Description IE content shall be encoded as shown in Table 4z.

Table 4z—Operating Mode Information field encoding for RCC PHY

Bit number	Description
0–3	The operating band selected. The bands are defined as the integers greater than zero that correspond to the bit numbers given in Table 4wa.
4–6	The channel number, as defined in Table 68m.
17–20	Modulation selection 0 = GMSK 9.6 kbps 1 = GMSK 19.2 kbps 2 = C4FM 9.6 kbps 3 = C4FM 19.2 kbps 4 = C4FM 38.4 kbps 5 = QPSK 16 kbps 6 = QPSK 32 kbps 7 = Pi/4 DQPSK 16 bps 8 = Pi/4 DQPSK 32 bps 9 = Pi/4 DQPSK 36 bps 10 = DSSS DPSK 11–15 = Reserved
21–23	Chip rate selection for DSSS DPSK 0 = 300 kcps 1 = 600 kcps 2 = 800 kcps 3 = 1 Mcps 4 = 1.6 Mcps 5 = 2 Mcps 6 = 3 Mcps 7 = 4 Mcps

Table 4z—Operating Mode Information field encoding for RCC PHY

Bit number	Description
24–26	Spreading sequence selection 0 = 11-chip 1 = 15-chip 2 = 20-chip 3 = 40-chip 4–7 = Reserved
21–31	Reserved

8. General PHY requirements

8.1 General requirements and definitions

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

— **RCC PHY:** a PHY operating at multiple over-the-air data rates in support of rail communications and control (RCC) applications, as defined in Clause 21, that supports the following five modulation schemes: Gaussian minimum shift keying (GMSK), continuous four-level frequency modulation (C4FM), quadrature phase-shift keying (QPSK), pi/4 differential quadrature phase-shift keying (Pi/4 DQPSK), and direct sequence spread spectrum (DSSS) employing differential phase-shift keying (DPSK).

8.1.1 Operating frequency range

Change the first paragraph of 8.1.1 as indicated, and insert the new table (Table 66c):

<Editor's note: the following paragraph is in the process of being modified by 15.4k. The text shown below is a modification to the 4k text.>

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

Table 66c—Frequency bands and data rates for RCC PHY

<table>
<tr><th>Band identifier</th><th>Frequency range
(MHz)</th><th>Modulation and bit rate</th></tr>
<tr><td>161</td><td>160.170–161.580</td><td rowspan="10">GMSK: 9.6/19.2 kbps
C4FM: 9.6/19.2/38.4 kbps
QPSK: 16/32 kbps
Pi/4 DQPSK: 16/32/36 kbps</td></tr>
<tr><td>216</td><td>216–217</td></tr>
<tr><td>217</td><td>217–220</td></tr>
<tr><td>220</td><td>220–222</td></tr>
<tr><td>450</td><td>450–470</td></tr>
<tr><td>770</td><td>769–775</td></tr>
<tr><td>800</td><td>799–805</td></tr>
<tr><td>806</td><td>806–821
851–866</td></tr>
<tr><td>896</td><td>896–901
935–940</td></tr>
<tr><td>901</td><td>901–902</td></tr>
</table>

Table 66c—Frequency bands and data rates for RCC PHY

Band identifier	Frequency range (MHz)	Modulation and bit rate
915	902–928	GMSK: 9.6/19.2 kbps C4FM: 9.6/19.2/38.4 kbps QPSK: 16/32 kbps Pi/4 DQPSK: 16/32/36 kbps DSSS DPSK
928	928–960	GMSK: 9.6/19.2 kbps C4FM: 9.6/19.2/38.4 kbps QPSK: 16/32 kbps Pi/4 DQPSK: 16/32/36 kbps
4965	4940–4990	DSSS DPSK
5300	5250–5350	
5600	5470–5725	
5800	5725–5850	

Insert the following new paragraph following the last paragraph of 8.1.1:

In the USA, devices operating in the 5300 MHz and 5600 MHz bands under FCC Title 47 CFR 15 Subpart E Unlicensed National Information Infrastructure employ both Transmit Power Control and Dynamic Frequency Selection, as per section 15.407.

8.1.2 Channel assignments

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

Change the first paragraph of 8.1.2.2 as indicated:

<Editor's note: the following paragraph is in the process of being modified by 15.4k. The text shown below is a modification to the 4k text.>

This subclause does not apply to the SUN PHY, ~~or~~ LECIM PHY, or RCC PHY specifications. For explanations of channel numbering for the SUN PHYs and LECIM PHYs, see 8.1.2.9 and 8.1.2.14, respectively. For an explanation of channel numbering for the RCC PHY, see 8.1.2.14.

Insert the following new subclause (8.1.2.14) after 8.1.2.13:

8.1.2.14 Channel numbering for RCC PHY

A channel page (*phyCurrentPage;* 9.3) value of 13 indicates the RCC PHY.

The channel center frequency, *ChanCenterFreq*, for the RCC PHY shall be derived as follows:

$$ChanCenterFreq = ChanCenterFreq_0 + NumChan \times ChanSpacing$$

where

ChanCenterFreq₀ is the first channel center frequency in MHz

ChanSpacing is the separation between adjacent channels in MHz

NumChan is the channel number from 0 to *TotalNumChan*–1

TotalNumChan is the total number of channels for the available frequency band

The parameters *ChanSpacing*, *TotalNumChan*, and $ChanCenterFreq_0$ for each frequency band is specified in Table 68m. The information in the table applies to all RCC modulation schemes.

Table 68m—Total number of channels and first channel center frequencies for RCC PHY

Band identifier	*ChanSpacing* (MHz)	*TotalNumChan*	$ChanCenterFreq_0$ (MHz)
161	0.0075	187	160.1775
216	0.00625	159	216.00625
217	0.00625	479	217.00625
220	0.005	400	220.0025
450	0.00625	3199	450.00625
770	0.00625	960	769.003125
800	0.00625	960	799.003125
806	As defined in US CFR Title 47 (FCC), Part 90, Subpart S, section 90.613		
896	As defined in US CFR Title 47 (FCC), Part 90, Subpart S, section 90.613		
901	0.0125	79	901.0125
915	0.500	51	902.500
928	0.00625	5119	928.0125
4965	As defined in US CFR Title 47 (FCC), Part 90, Subpart Y, section 90.1213		
5300	0.5	199	5250.5
5600	0.5	499	5475.5
5800	0.5	249	5725.5

8.1.3 Minimum LIFS and SIFS periods

Change the first paragraph of 8.1.3 as indicated:

For all PHYs other than the UWB and RCC PHYs, the minimum LIFS period and SIFS period are:[1]

— *macLIFSPeriod* – 40 symbols

— *macSIFSPeriod* – 12 symbols

[1]For the MR-OFDM PHY, the MAC symbol duration is defined in 5.1.

Insert the following new paragraph after the first paragraph of 8.1.3:

For the RCC PHY, the minimum LIFS period and SIFS period are:

— *macLIFSPeriod* – 5 symbols

— *macSIFSPeriod* – 5 symbols

8.2 General radio specifications

8.2.7 Clear channel assessment (CCA)

Change the third paragraph of 8.2.7 as indicated:

The PHY PIB attribute *phyCCAMode*, as described in 9.3, shall indicate the appropriate operation mode. The CCA parameters are subject to the following criteria:

a) Except for the MR-O-QPSK PHY, the ED threshold shall correspond to a received signal power of at most 10 dB greater than the specified receiver sensitivity for that PHY. For the MR-O-QPSK PHY, the ED threshold shall comply with the specification in 16.3.4.13.

b) Except for the 920 MHz band PHYs, ~~and~~ the 950 MHz band PHYs, and the RCC PHY, the CCA detection time shall be equal to *aCCATime*, as defined in Table 70. For the 920 MHz band, ~~and~~ the 950 MHz band PHYs, and the RCC PHY, *phyCCADuration* symbol periods shall be used.

9. PHY services

9.2 PHY constants

<Editor's note: the constant aMaxPHYPacketSize is in the process of being modified by 15.4k. The text shown is a modification to the 4k text.>

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

Table 70—PHY constants

Constant	Description	Value
aMaxPHYPacketSize	The maximum PSDU size (in octets) the PHY shall be able to receive.	2047 for SUN, ~~and~~ LECIM FSK, and RCC PHYs. For LECIM DSSS PHY, this is not a constant; refer to *phyLECIMDSSSPSDUSize*. 127 for all other PHYs

9.3 PHY PIB attributes

Change Table 71 (the entire table is not shown) as indicated:

Table 71—PHY PIB attributes

Attribute	Type	Range	Description
phyCCADuration	Integer	0–1000	The duration for CCA, specified in symbols. This attribute shall only be implemented with PHYs operating in the 920 MHz band and the 950 MHz band, and with the RCC PHY.

Insert after Clause 20 the following new clause (Clause 21):

21. RCC PHY

A PHY with five possible modulation schemes is specified in order to support RCC applications. The five supported modulations schemes are GMSK, as described in 21.5.1; C4FM, as described in 21.5.2; QPSK, as described in 21.5.3; and Pi/4 DQPSK, as described in 21.5.4; and DSSS employing DPSK, as described in 21.5.5.

21.1 PPDU format

The RCC PHY PPDU shall be formatted as illustrated in Figure 154.

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

Bits: 32/64	23			0/6	variable			0/3
	Data FEC Type (4 bits)	Data Length (11 bits)	CRC (8 bits)	PHR FEC Tail	PSDU (variable)	Payload FEC Tail (0/6 bits)	PAD (variable)	
SHR	PHR				PHY payload			GMSK tail

Figure 154—Format of the RCC PPDU

21.1.1 SHR

The SHR shall be selected from the list of values shown in Table 72. The SHR is transmitted starting from the left-most bit.

Table 72—SHR values for RCC PHY

Modulation	SHR value for FEC coded PHR	SHR value for FEC uncoded PHR
GMSK 9.6/19.2 kbps	1111 1000 0011 1000 1001 0000 1110 1101	0000 0111 1100 0111 0110 1111 0001 0010
C4FM 9.6/19.2/38.4 kbps	0101 0101 0111 1111 1111 01 0101 1111 1101 1111 0111 11 1111 0101 0111 0101 1101	1111 1111 1101 0101 0101 11 1111 0101 0111 0101 1101 01 0101 1111 1101 1111 0111
QPSK 16/32 Kbps	1100 1100 1100 1100 1100 11 1111 0000 0011 0000 1100 00 0000 1111 1100 1111 0011	1100 1100 1100 1100 1100 11 1111 0000 0011 0000 1100 11 1111 0000 0011 0000 1100
Pi/4 DQPSK 16/32 Kbps	0101 0101 0111 1111 1111 01 0101 1111 1101 1111 0111 11 1111 0101 0111 0101 1101	1111 1111 1101 0101 0101 11 1111 0101 0111 0101 1101 01 0101 1111 1101 1111 0111

Table 72—SHR values for RCC PHY

Modulation	SHR value for FEC coded PHR	SHR value for FEC uncoded PHR
DSSS DBPSK	1010 1010 1011 1000 1001 0000 1110 1101	10 1010 1011 1000 1001 0111 0001 0010
DSSS DQPSK	1100 1100 1100 1100 1100 11 1111 0000 0011 0000 1100 00 0000 1111 1100 1111 0011	1100 1100 1100 1100 1100 11 1111 0000 0011 0000 1100 11 1111 0000 0011 0000 1100

21.1.2 PHR header

The Data FEC Type field indicates the coding rate used in the PSDU field, and it shall be assigned according to Table 73; see 21.2 for more information on coding. The left most bit shall be transmitted first.

Table 73—Data FEC Type field for RCC PHY

Data FEC Type field value	Coding rate
0000	1 (no FEC)
0001	7/8
0010	3/4
0011	2/3
0100	1/2
0101–1111	Reserved

The Data Length field specifies the total number of octets contained in the PSDU. The MSB shall be transmitted first.

The Data FEC Type and Data Length fields shall be protected with an 8-bit CRC. The CRC shall be the remainder generated by the modulo 2 division of the protected fields by the polynomial:

$$x^8 + x^2 + x + 1$$

The protected bits shall be processed in transmit order. All CRC calculations shall be made prior to data whitening. A schematic of the processing is shown in Figure 155.

When FEC is applied to the PHR, the PHR FEC Tail field shall have a length of 6 bits (i.e., six FEC tail bits are appended after the CRC field to aid in FEC decoding). When the PHY header is not FEC protected, the PHR FEC Tail field shall have length zero (i.e., no tail bits are appended).

21.1.3 PHY payload

The Data FEC Type field determines whether the PSDU is FEC protected. The Payload FEC Tail field shall be present only if the PSDU is FEC protected.

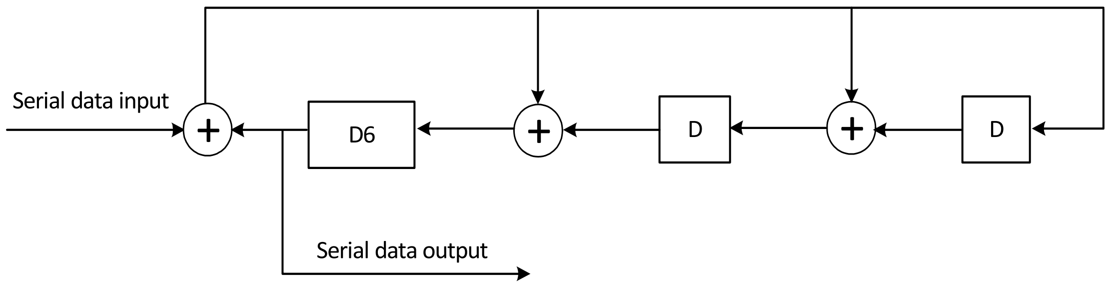

Figure 155—CRC-8 implementation for RCC PHY

The length of the PAD field depends on the selected coding rate. The total number of bits contained in the PSDU, Payload FEC Tail, and PAD fields shall be an integer multiple of the puncturing pattern according to Figure 157.

21.1.4 GMSK tail

Three extra zero bits are appended at the end of the packet for Gaussian filter response time if GMSK modulation is used. No GMSK tail bits shall be appended for other modulation modes.

21.2 Forward error correction (FEC)

FEC protection of the PHR shall be supported. When FEC is enabled, a ½ code rate convolutional code shall be used.

The PSDU shall be coded using one of the values contained in Table 73, corresponding to the desired data rate. The convolutional encoder shall use generator polynomials $g_0 = 133_8$ and $g_1 = 171_8$ for rate ½, as shown in Figure 156. Higher rates are achieved by puncturing, according to Figure 157.

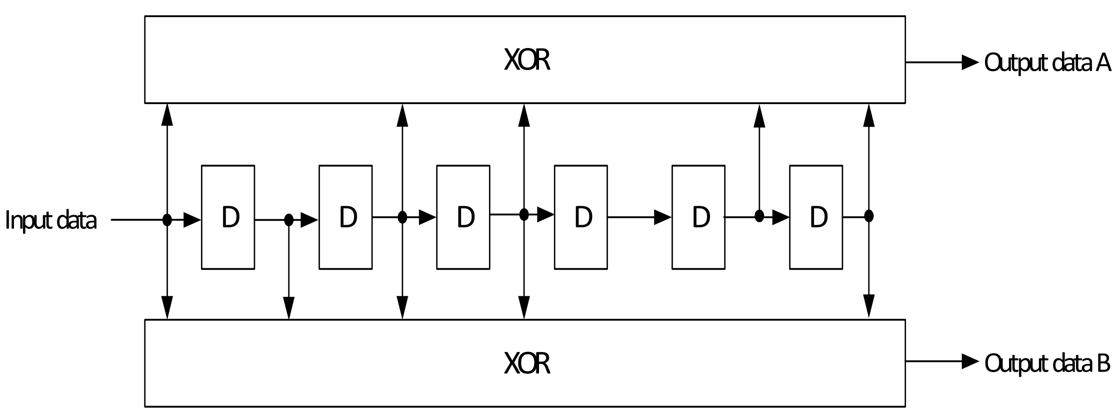

Figure 156—Convolutional encoder for RCC PHY

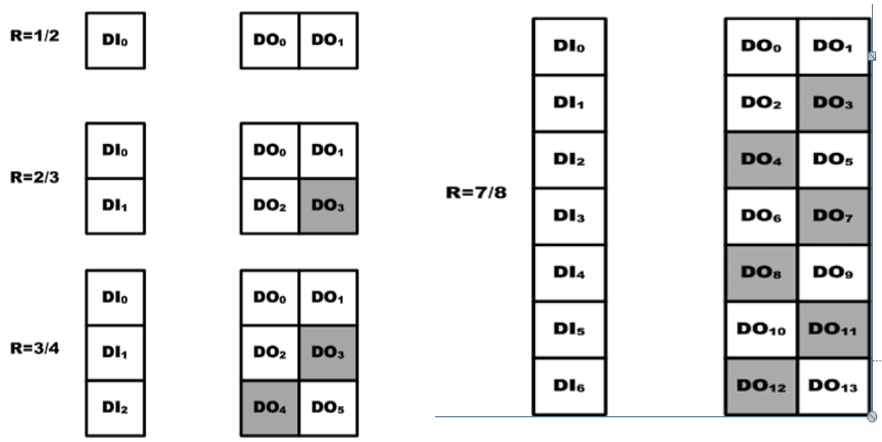

Figure 157—FEC puncturing pattern for RCC PHY

21.3 Interleaver

Interleaving of the PHY payload shall be supported. Interleaving may be enabled when FEC is enabled. Interleaving shall be disabled when FEC is disabled.

The process of interleaving is illustrated in Figure 158.

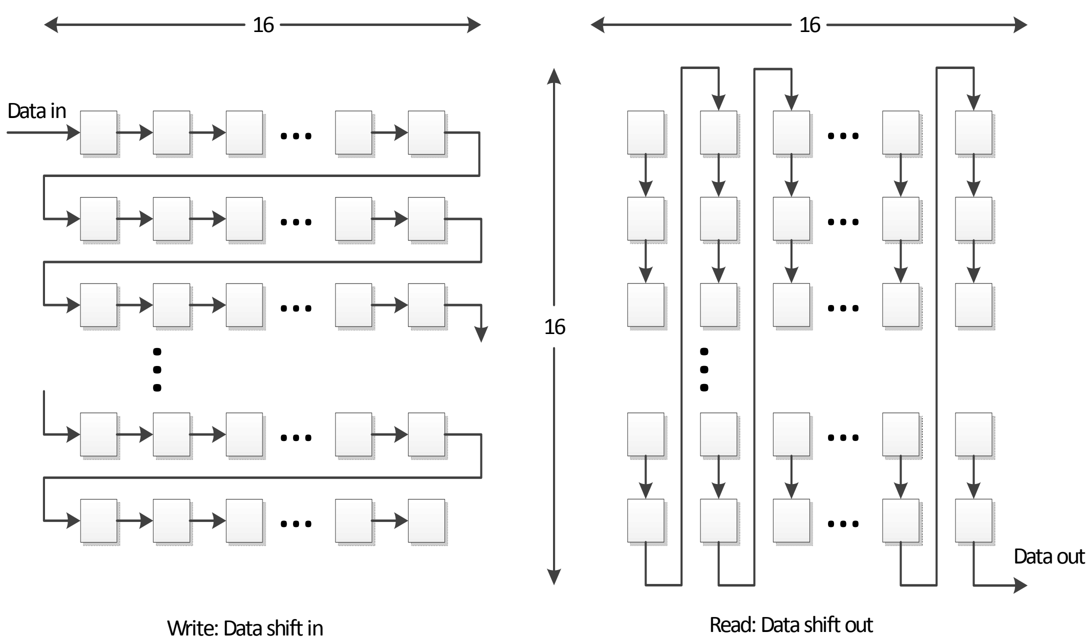

Figure 158—Interleaver for RCC PHY

21.4 Data whitening

Data whitening shall be applied to the PHR and PHY payload. See 16.1.3 for more details.

The PN9 sequence generator shall not be reset between the PHR and the PSDU.

21.5 Modulation

The modulation scheme and data rate shall be configured using the RCC PHY Operating Mode Description IE, as described in 5.2.4.29.3.

21.5.1 GMSK

GMSK is MSK modulation with Gaussian filtering. MSK is a special case of continuous phase FSK, and its modulation index is exactly 0.5.

The modulated waveform may be represented as:

$$s(t) = A\cos(\omega_0 t + \phi(t))$$

where

A is the signal amplitude

ω_0 is the carrier angular frequency

$\phi(t)$ is the signal phase

The signal phase $\phi(t)$ may be represented by the data bit stream d_0, d_1, d_2 ... as:

$$\phi(t) = \phi_0 + \frac{\pi}{2}\int\left[G(t)*\sum_i k_i \mathrm{rect}(t - iT)\right]dt$$

where

$$G(t) = \frac{1}{\sigma T\sqrt{2\pi}}\exp\left(\frac{-t^2}{2\sigma^2 T^2}\right) \text{ with } \sigma = \frac{\sqrt{\ln(2)}}{2\pi BT}$$

$$k_i = \begin{cases} 1 & \text{if } d_i = 1 \\ -1 & \text{if } d_i = 0 \end{cases}$$

$$\mathrm{rect}(t) = \begin{Bmatrix} (1/T) & \text{for } 0 < t < T \\ 0 & \text{otherwise} \end{Bmatrix}$$

T is the symbol period

ϕ_0 is the initial phase

The initial phase ϕ_0 may take any value. It is not specified and is, therefore, unknown to the receiver.

Figure 159 shows a typical GMSK modulation in digital implementation. This functional block diagram serves as a reference for specifying the RCC PHY with GMSK modulation.

Data "1" shall have positive frequency deviation. Data "0" shall have negative frequency deviation.

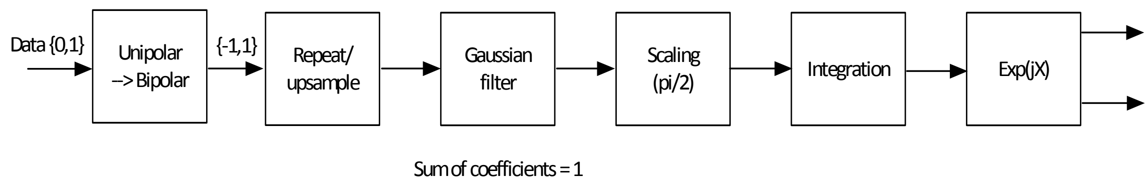

Figure 159—Typical GMSK modulator for RCC PHY

The default BT value shall be 0.3, since it provides good adjacent channel power ratio in order to meet spectrum masks in narrow band applications such as US FCC Part 90. Lower BT values provide narrower spectrum width, but the eye opening is narrower and may degrade receiver decoding. A larger BT may optionally be used where regulations permit. Typical power spectrum density of MSK and GMSK is shown in Figure 160. The eye diagrams are shown in Figure 161, Figure 162, and Figure 163.

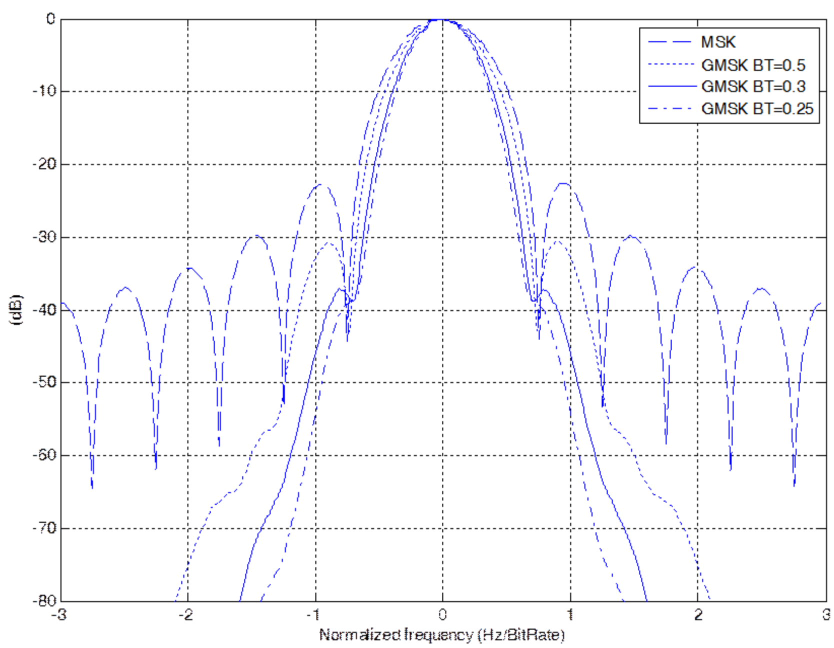

Figure 160—Typical GMSK power spectrum density

21.5.2 C4FM

C4FM is a four-level frequency modulation with continuous phase. Figure 164 shows a typical C4FM modulator in digital implementation. This functional block diagram serves as a reference for specifying the RCC PHY with C4FM modulation.

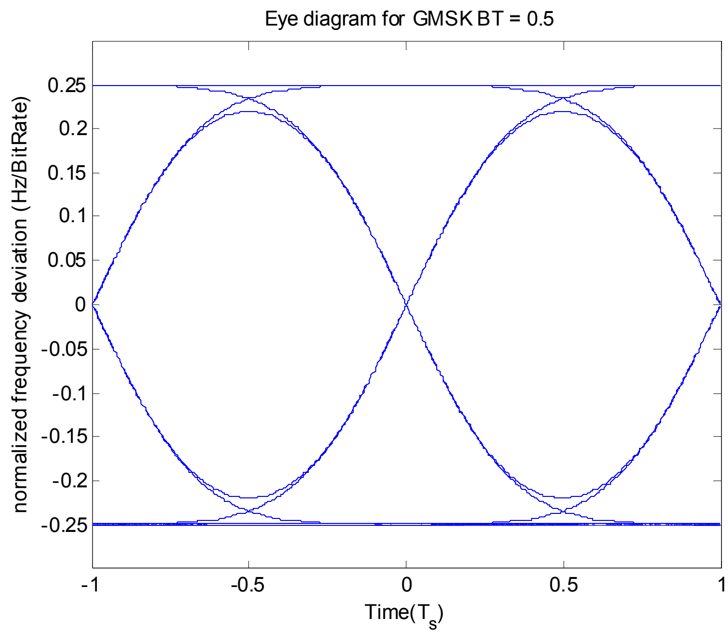

Figure 161—Eye diagram for GMSK with BT=0.5

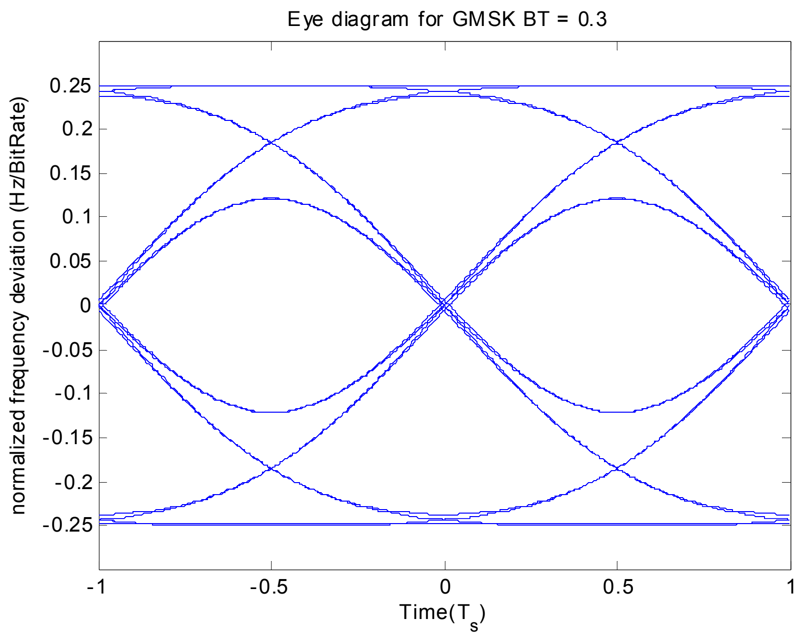

Figure 162—Eye diagram for GMSK with BT=0.3

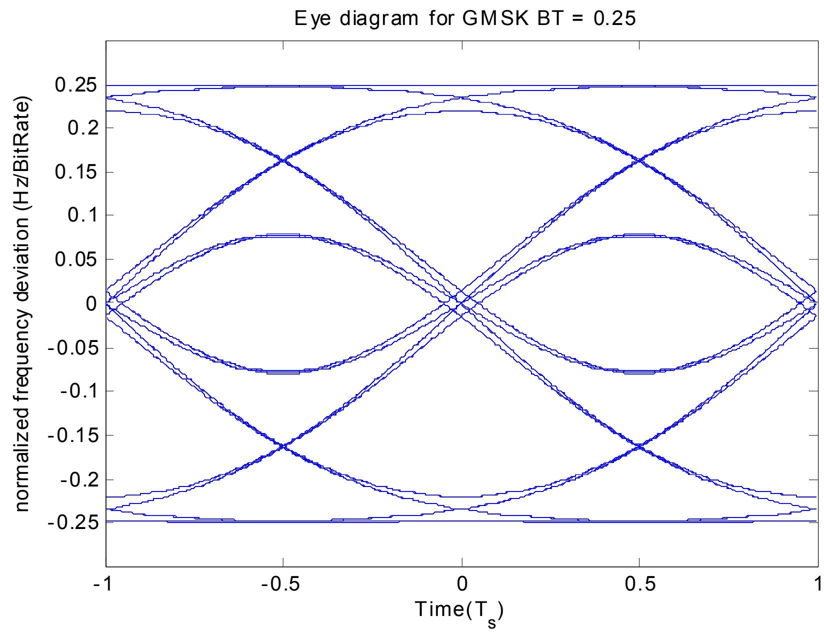

Figure 163—Eye diagram for GMSK with BT=0.25

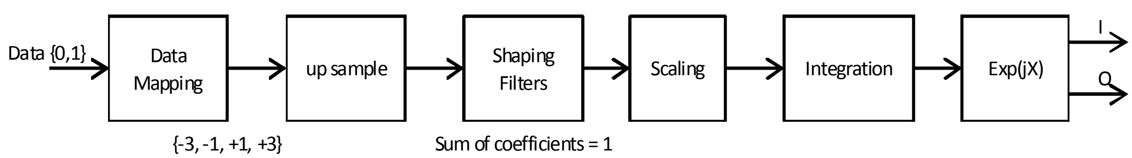

Figure 164—Typical C4FM modulator for RCC PHY

The shaping filters consists of a Nyquist raised cosine filter cascaded with an inverse-sinc filter. The frequency response of the Nyquist raised cosine filter *H(f)* is given by:

$$|H(f)| = 1, \qquad \text{for } |f| < \text{symbol rate} \times 0.4$$

$$|H(f)| = 0.5 + 0.5\cos\left[\frac{2 \times \text{pi} \times f}{\text{symbol rate} \times 0.4}\right], \qquad \text{for } (\text{symbol rate} \times 0.4) < |f| < (\text{symbol rate} \times 0.6)$$

$$|H(f)| = 0, \qquad \text{for } (|f| > \text{symbol rate} \times 0.6)$$

The group delay of the Nyquist raised cosine filter is flat over the pass band for $|f| < \text{symbol rate} \times 0.6$.

The amplitude response of the inverse-sinc filter *P(f)* is given by:

$$|P(f)| = \left[\frac{\left(\frac{\text{pi} \times f}{\text{symbol rate}}\right)}{\left(\frac{\sin(\text{pi} \times f)}{\text{symbol rate}}\right)}\right], \quad \text{for } |f| < (\text{symbol rate} \times 0.6)$$

The response of *P(f)* for $|f| > \text{symbol rate} \times 0.6$ is not specified for frequencies above $\text{symbol rate} \times 0.6$, since these frequencies are cut off by *H(f)*.

The data mapping and frequency deviation is indicated in Table 74. The value of the scaling block shown in Figure 164 should be chosen properly to match the corresponding frequency deviation.

Table 74—C4FM frequency deviation for RCC PHY

Data $\{b_1, b_0\}$	Frequency deviation (normalize to symbol rate)
01	+3/8
00	+1/8
10	–1/8
11	–3/8

21.5.3 QPSK

Figure 165 shows a typical QPSK modulator in digital implementation. This functional block diagram serves as a reference for specifying the RCC PHY with QPSK modulation. The bit-to-symbol mapping shall be encoded according to Figure 166. The default pulse shaping filter shall be a root cosine filter with a roll-off factor of 0.25.

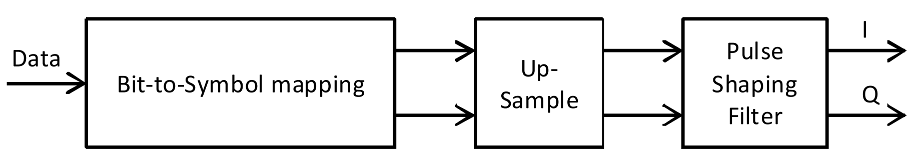

Figure 165—Typical QPSK modulator for RCC PHY

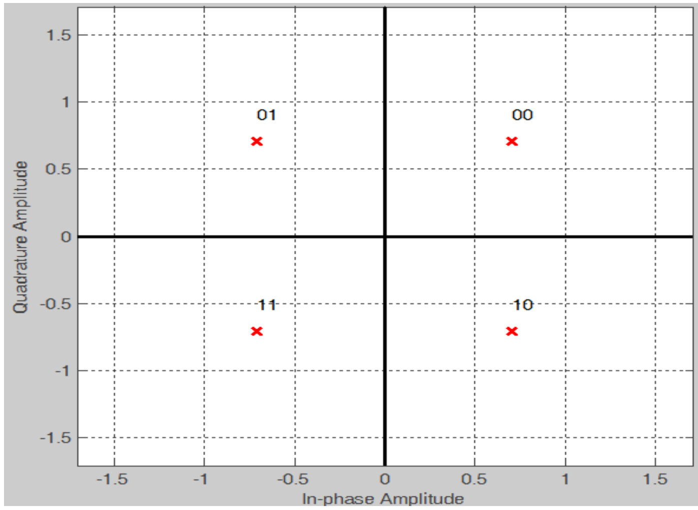

Figure 166—Bit-to-symbol mapping for QPSK (RCC PHY)

21.5.4 Pi/4 DQPSK

Figure 167 shows a typical Pi/4 DQPSK modulator in digital implementation. This functional block diagram is provided as a reference for specifying the RCC PHY using Pi/4 DQPSK modulation. The bit-to-symbol mapping and differential encoding shall be encoded according to Table 75. The default pulse shaping filter shall be a root raised cosine filter with a roll-off factor of 0.25.

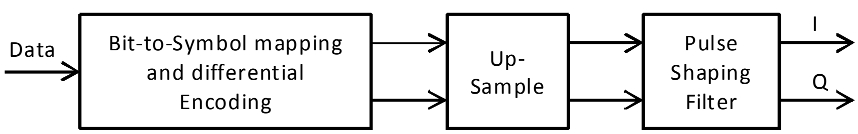

Figure 167—Typical Pi/4 DQPSK modulator for RCC PHY

Table 75—Pi/4 DQPSK encoding values for RCC PHY

Data $\{b_1, b_0\}$	Phase change
01	$+3/4 \times$ pi
00	$+1/4 \times$ pi
10	$-1/4 \times$ pi
11	$-3/4 \times$ pi

A typical power spectrum density is shown in Figure 168. The spectrum skirt is caused by time domain truncation of the shaping pulse and is design dependent.

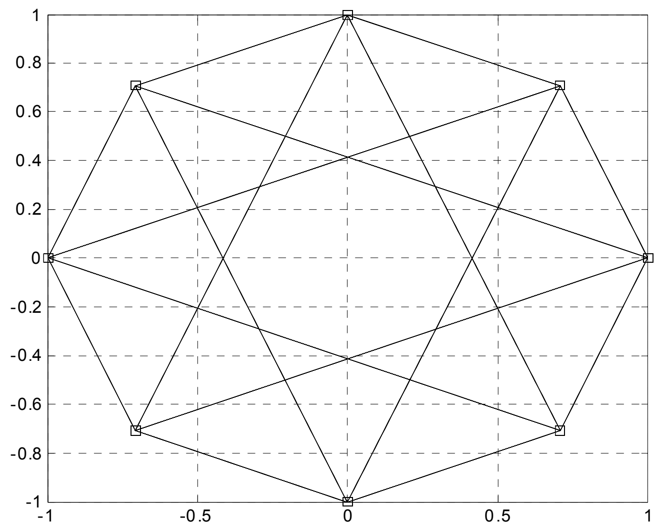

Figure 168—Signal constellation of Pi/4 DQPSK for RCC PHY

21.5.5 DSSS DPSK

The modulation for DSSS DPSK is either DSSS DBPSK or DSSS DQPSK.

The functional block diagram shown in Figure 169 is provided as a reference for specifying the DSSS DPSK modulation and spreading functions.

Figure 169—DSSS DQPSK modulation and spreading

The bit-to-symbol mapping and differential encoding for DSSS DBPSK shall be encoded according to Table 76.

Table 76—DSSS DBPSK encoding table

Data	Phase change
0	0
1	pi

The bit-to-symbol mapping and differential encoding for DSSS DQPSK shall be encoded according to Table 77.

Table 77—DSSS DQPSK encoding table

Dibit pattern (d_0,d_1)*	Phase change
00	0
01	$\frac{pi}{2}$
11	pi
10	$-\frac{pi}{2}$

*Bit d_0 is transmitted first in time.

The spreading sequences are specified in Table 78. The leftmost chip shall be output first in time.

Table 78—DSSS DPSK spreading sequences

Spreading sequence length	Spreading sequence
11	111 0001 0010
15	101 1111 0100 0110
20	1010 1000 0011 0110 0111
40	1010 0011 1001 0010 1101 1101 1001 1010 1011 1111

The chip rates are specified in Table 79.

Table 79—DSSS DPSK chip rates

DSSS DPSK chip rates
300 kcps
600 kcps
800 kcps
1 Mcps
1.6 Mcps
2 Mcps

Table 79—DSSS DPSK chip rates

DSSS DPSK chip rates
3 Mcps
4 Mcps

21.6 Reference modulator diagram

The functional block diagram in Figure 170 serves as a reference for specifying the RCC PHY data flow processing functions. Data whitening shall be applied over the PHR and PHY payload continuously. The six FEC tail bits shall be replaced by six non-scrambled zeros prior to FEC encoding. When FEC is enabled, FEC processing for the PHR and PHY payload shall be performed separately.

All fields in the PPDU shall use the same symbol rate and modulation.

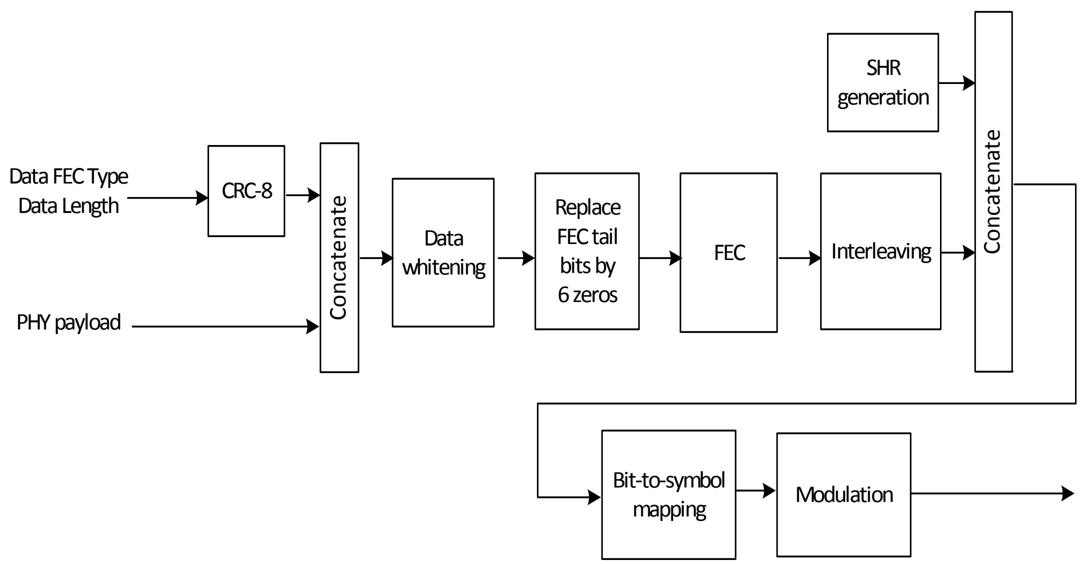

Figure 170—RCC PHY reference modulator diagram

21.7 RCC PHY RF requirements

21.7.1 Radio frequency tolerance

The center frequency error shall confirm with local regulations or be less than or equal to ±1 ppm, whichever is tighter.

21.7.2 Transmitter symbol rate tolerance

The transmitter symbol rate error shall be less than or equal to ±1 ppm.

21.7.3 Channel switching time

The channel switching time shall be less than or equal to 500 μs .

21.7.4 Transmit power spectral density (PSD) mask

The RCC PHY transmit spectral mask shall conform with local regulations.

21.7.5 Error vector magnitude

When the RCC PHY is using either QPSK or Pi/4 DQPSK modulation, it shall have EVM values of less than 35% when measured for 1000 symbols using the measurement process defined in 8.2.3.

21.7.6 Transmit power

The maximum transmit power is limited by local regulatory bodies.

21.7.7 Receiver sensitivity

Receiver sensitivity is implementation specific, however, the method for measuring receiver sensitivity is described in 8.1.7.

21.7.8 Receiver interference rejection

The minimum receiver interference rejection is implementation specific.

21.7.9 Receiver maximum input level of desired signal

The receiver maximum input level is implementation specific.

21.7.10 TX-to-RX turnaround time

The TX-to-RX turnaround time shall be less than or equal to 500 μs .

21.7.11 RX-to-TX turnaround time

The RX-to-TX turnaround time shall be less than or equal to 500 μs .

21.7.12 Receiver energy detection (ED)

The RCC PHY shall provide the receiver ED measurement, as described in 8.2.5.

21.7.13 Link quality indicator (LQI)

The RCC PHY shall provide the LQI measurement, as described in 8.2.6.

21.7.14 Clear channel assessment (CCA)

The RCC PHY shall use one of the CCA methods described in 8.2.7.

Annex D

(informative)

Protocol implementation conformance statement (PICS) proforma[2]

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

D.2 Abbreviations and special symbols

Notations for requirement status:

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

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

D.7 PICS proforma tables

D.7.1 Functional device types

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

Table D.1—Functional device types

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
FD10	RCC PHY device	8.1	O.3			
O.3: At least one of these features is supported.						

D.7.2 Major capabilities for the PHY

D.7.2.1a PHY packet

[2]Copyright release for PICS proformas: Users of this standard may freely reproduce the PICS proforma in this annex so that it can be used for its intended purpose and may further publish the completed PICS.

Change Table D.2a as indicated:

Table D.2a—PHY packet

Item number	Item description	Reference	Status	Support		
				N/A	Yes	No
PLP1	PSDU size up to 2047 octets	9.2	FD6, FD10: M			

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
RF21	RCC PHYs					
RF21.1	GMSK	21.5.1	FD10: O.11			
RF21.2	C4FM	21.5.2	FD10: O.11			
RF21.3	QPSK	21.5.3	FD10: O.11			
RF21.4	Pi/4 DQPSK	21.5.4	FD10: O.11			
RF21.5	DSSS DPSK	21.5.5	FD10: O.11			
RF21.6	At least one of the bands given in Table 66c	8.1	FD10: M			
RF21.7	FEC	21.2	FD10: M			
RF21.8	Interleaving	21.3	FD10: M			
RF21.9	Data whitening	21.4	FD10: M			
O.11: At least one of these modulation schemes is supported.						