IEEE P802.15

Wireless Personal Area Networks

Project	IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)
Title	Preliminary document for TG4p
Date Submitted	31 January 2013
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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.

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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): TBD

3.2 Acronyms and abbreviations

Insert the following acronyms alphabetically into 3.2:

C4FM	continuous four-level frequency modulation
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
RC	rail communications

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4. General description

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

4.1b Introduction to positive train control (PTC)

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 positive train control (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.

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5. MAC protocol

5.1 MAC functional description

TBD

5.2 MAC frame formats

TBD

5.3 MAC command frames

TBD

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6. MAC services

6.1 Overview

TBD

6.2 MAC management service

TBD

6.3 MAC data service

TBD

6.4 MAC constants and PIB attributes

TBD

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8. General PHY requirements

8.1 General requirements and definitions

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

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

8.1.1 Operating frequency range

Insert the following new rows at the end of Table 66:

Table 66—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
161	160.170–161.580	—	GMSK	9.6	9.6	Binary
		—	GMSK	19.2	19.2	Binary
		—	C4FM	9.6	4.8	4-ary
		—	C4FM	19.2	9.6	4-ary
		—	C4FM	38.4	19.2	4-ary
		—	QPSK	16	8	4-ary
		—	QPSK	32	16	4-ary
		—	Pi/4 DQPSK	16	8	4-ary
		—	Pi/4 DQPSK	32	16	4-ary
217	217–220	—	GMSK	9.6	9.6	Binary
		—	GMSK	19.2	19.2	Binary
		—	C4FM	9.6	4.8	4-ary
		—	C4FM	19.2	9.6	4-ary
		—	C4FM	38.4	19.2	4-ary
		—	QPSK	16	8	4-ary
		—	QPSK	32	16	4-ary
		—	Pi/4 DQPSK	16	8	4-ary
		—	Pi/4 DQPSK	32	16	4-ary

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Table 66—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
220	220–222	—	GMSK	9.6	9.6	Binary
		—	GMSK	19.2	19.2	Binary
		—	C4FM	9.6	4.8	4-ary
		—	C4FM	19.2	9.6	4-ary
		—	C4FM	38.4	19.2	4-ary
		—	QPSK	16	8	4-ary
		—	QPSK	32	16	4-ary
		—	Pi/4 DQPSK	16	8	4-ary
		—	Pi/4 DQPSK	32	16	4-ary
450	450–470	—	GMSK	9.6	9.6	Binary
		—	GMSK	19.2	19.2	Binary
		—	C4FM	9.6	4.8	4-ary
		—	C4FM	19.2	9.6	4-ary
		—	C4FM	38.4	19.2	4-ary
		—	QPSK	16	8	4-ary
		—	QPSK	32	16	4-ary
		—	Pi/4 DQPSK	16	8	4-ary
		—	Pi/4 DQPSK	32	16	4-ary
700	TBD	—	GMSK	9.6	9.6	Binary
		—	GMSK	19.2	19.2	Binary
		—	C4FM	9.6	4.8	4-ary
		—	C4FM	19.2	9.6	4-ary
		—	C4FM	38.4	19.2	4-ary
		—	QPSK	16	8	4-ary
		—	QPSK	32	16	4-ary
		—	Pi/4 DQPSK	16	8	4-ary
		—	Pi/4 DQPSK	32	16	4-ary

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Table 66—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
800	TBD	—	GMSK	9.6	9.6	Binary
		—	GMSK	19.2	19.2	Binary
		—	C4FM	9.6	4.8	4-ary
		—	C4FM	19.2	9.6	4-ary
		—	C4FM	38.4	19.2	4-ary
		—	QPSK	16	8	4-ary
		—	QPSK	32	16	4-ary
		—	Pi/4 DQPSK	16	8	4-ary
		—	Pi/4 DQPSK	32	16	4-ary
896	896–901	—	GMSK	9.6	9.6	Binary
		—	GMSK	19.2	19.2	Binary
		—	C4FM	9.6	4.8	4-ary
		—	C4FM	19.2	9.6	4-ary
		—	C4FM	38.4	19.2	4-ary
		—	QPSK	16	8	4-ary
		—	QPSK	32	16	4-ary
		—	Pi/4 DQPSK	16	8	4-ary
		—	Pi/4 DQPSK	32	16	4-ary
901	902	—	GMSK	9.6	9.6	Binary
		—	GMSK	19.2	19.2	Binary
		—	C4FM	9.6	4.8	4-ary
		—	C4FM	19.2	9.6	4-ary
		—	C4FM	38.4	19.2	4-ary
		—	QPSK	16	8	4-ary
		—	QPSK	32	16	4-ary
		—	Pi/4 DQPSK	16	8	4-ary
		—	Pi/4 DQPSK	32	16	4-ary

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Table 66—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
915	902–928	—	GMSK	9.6	9.6	Binary
		—	GMSK	19.2	19.2	Binary
		—	C4FM	9.6	4.8	4-ary
		—	C4FM	19.2	9.6	4-ary
		—	C4FM	38.4	19.2	4-ary
		—	QPSK	16	8	4-ary
		—	QPSK	32	16	4-ary
		—	Pi/4 DQPSK	16	8	4-ary
		—	Pi/4 DQPSK	32	16	4-ary
928	928–960	—	GMSK	9.6	9.6	Binary
		—	GMSK	19.2	19.2	Binary
		—	C4FM	9.6	4.8	4-ary
		—	C4FM	19.2	9.6	4-ary
		—	C4FM	38.4	19.2	4-ary
		—	QPSK	16	8	4-ary
		—	QPSK	32	16	4-ary
		—	Pi/4 DQPSK	16	8	4-ary
		—	Pi/4 DQPSK	32	16	4-ary
4965	4940–4990	—	GMSK	9.6	9.6	Binary
		—	GMSK	19.2	19.2	Binary
		—	C4FM	9.6	4.8	4-ary
		—	C4FM	19.2	9.6	4-ary
		—	C4FM	38.4	19.2	4-ary
		—	QPSK	16	8	4-ary
		—	QPSK	32	16	4-ary
		—	Pi/4 DQPSK	16	8	4-ary
		—	Pi/4 DQPSK	32	16	4-ary

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Table 66—Frequency bands and data rates

<table>
<tr><th rowspan="2">PHY
(MHz)</th><th rowspan="2">Frequency band
(MHz)</th><th colspan="2">Spreading parameters</th><th colspan="3">Data parameters</th></tr>
<tr><th>Chip rate
(kchip/s)</th><th>Modulation</th><th>Bit rate
(kb/s)</th><th>Symbol rate
(ksymbol/s)</th><th>Symbols</th></tr>
<tr><td rowspan="9">5800</td><td rowspan="9">5725–5850</td><td>—</td><td>GMSK</td><td>9.6</td><td>9.6</td><td>Binary</td></tr>
<tr><td>—</td><td>GMSK</td><td>19.2</td><td>19.2</td><td>Binary</td></tr>
<tr><td>—</td><td>C4FM</td><td>9.6</td><td>4.8</td><td>4-ary</td></tr>
<tr><td>—</td><td>C4FM</td><td>19.2</td><td>9.6</td><td>4-ary</td></tr>
<tr><td>—</td><td>C4FM</td><td>38.4</td><td>19.2</td><td>4-ary</td></tr>
<tr><td>—</td><td>QPSK</td><td>16</td><td>8</td><td>4-ary</td></tr>
<tr><td>—</td><td>QPSK</td><td>32</td><td>16</td><td>4-ary</td></tr>
<tr><td>—</td><td>Pi/4 DQPSK</td><td>16</td><td>8</td><td>4-ary</td></tr>
<tr><td>—</td><td>Pi/4 DQPSK</td><td>32</td><td>16</td><td>4-ary</td></tr>
</table>

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 RC 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 RC 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 RC PHY

A channel page (*phyCurrentPage;* 9.3) value of X indicates the RC PHY.

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

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

where

$ChanCenterFreq_0$ 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 68l. The information in the table applies to all RC modulation schemes.

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Table 68l—Total number of channels and first channel center frequencies for RC PHY

PHY (MHz)	*ChanSpacing* (MHz)	*TotalNumChan*	*ChanCenterFreq*$_0$ *(MHz)*
161	0.0075	186	160.1775
217	0.0125	239	217.0125
220	0.0125	159	220.0125
450	0.0125	1599	450.0125
700	TBD	TBD	TBD
800	TBD	TBD	TBD
896	0.0125	399	896.0125
901	0.0125	2079	902.0125
915	0.500	2079	902.500
928	0.00625	2559	928.0125
4965	TBD	9	4940.5, 4941.5, 4942.5, 4943.5, 4944.5, 4986.5, 4987.8, 4988.5, 4989.5
5800	0.500	249	5725.500

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 RC PHYs, the minimum LIFS period and SIFS period are:[1]

— *macLIFSPeriod* – 40 symbols
— *macSIFSPeriod* – 12 symbols

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

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

— *macLIFSPeriod* – TBD symbols
— *macSIFSPeriod* – TBD symbols

8.1.7 Receiver sensitivity definitions

Change Table 69 (the entire table is not shown) as indicated:

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

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Table 69—Receiver sensitivity conditions

Term	Definition of term	Conditions
Receiver sensitivity	Lowest input power for which the PER conditions are met.	– PSDU length = 250 octets for SUN PHYs with data rates 50 kb/s and greater, ; 125 (TBD) octets for RC PHY; 20 octets for all other PHYs. – PER < 10% for SUN PHYs. – PER < 1% for all other PHYs. – Power measured at antenna terminals. – Interference not present.

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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 PHYs. For LECIM DSSS PHY, this is not a constant; refer to *phyLECIMDSSSPSDUSize*. TBD for RC PHY. 127 for all other PHYs

9.3 PHY PIB attributes

TBD

Table 71—PHY PIB attributes

Attribute	Type	Range	Description

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

21. RC PHY

A PHY with four possible modulation schemes is specified in order to support RC applications. The four 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.

21.1 PPDU format

The RC 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	**23/29**				**variable**			**0/3**
	Data FEC Type (4 bits)	Data Length (11 bits)	CRC (8 bits)	PHR FEC Tail (0/6 bits)	PSDU (variable)	Payload FEC Tail (0/6 bits)	PAD (variable)	
SHR	PHR				PHY payload			GMSK tail

Figure 154—Format of the RC 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 RC PHY

Modulation	**SHR value for FEC coded PHR**	**SHR value for FEC uncoded PHR**
GMSK 9.6 Kbps	TBD	TBD
GMSK 19.2 Kbps	TBD	TBD
C4FM 9.6 Kbps	TBD	TBD
C4FM 19.2 Kbps	TBD	TBD
C4FM 38.4 Kbps	TBD	TBD
QPSK 16 Kbps	TBD	TBD
QPSK 32 Kbps	TBD	TBD
Pi/4 DQPSK 16 Kbps	TBD	TBD
Pi/4 DQPSK 32 Kbps	TBD	TBD

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21.1.2 PHR header

FEC protection of the PHR shall be supported. A non-FEC protected PHY header may also be supported. When used, FEC shall be a ½ code rate convolutional code, as described in 21.2.

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

Table 73—Data FEC Type field for RC 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.

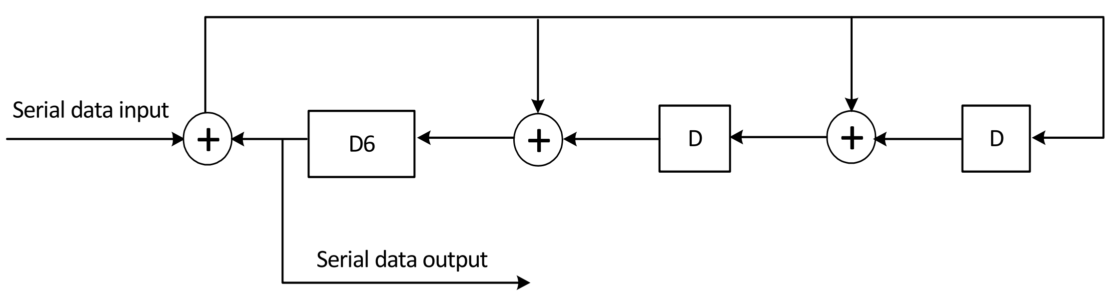

Figure 155—CRC-8 implementation for RC PHY

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).

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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.

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)

The PHR and 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.

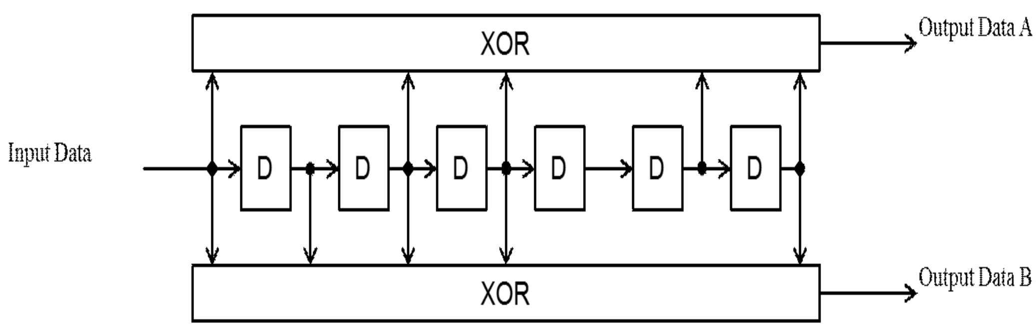

Figure 156—Convolutional encoder for RC PHY

21.3 Interleaver

Interleaving shall be supported for the PHY payload when FEC is enabled. A non-interleaved PHY payload may also be supported with FEC enabled. Interleaving shall be turned off when FEC is disabled.

The process of interleaving is illustrated in Figure 158.

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.

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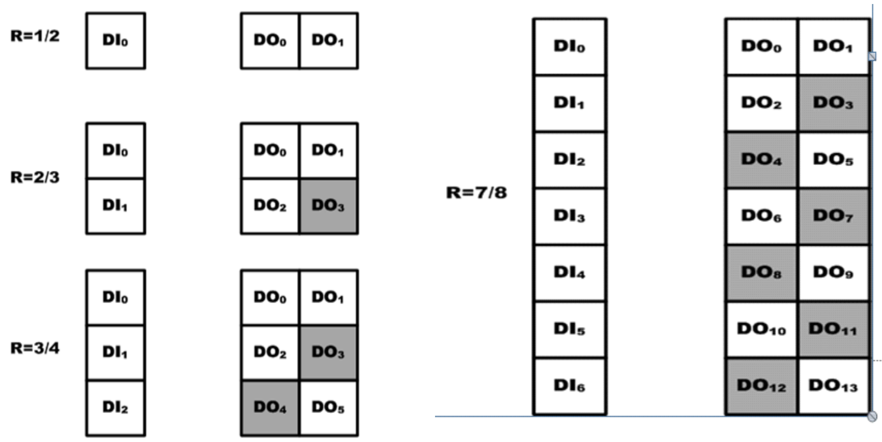

Figure 157—FEC puncturing pattern for RC PHY

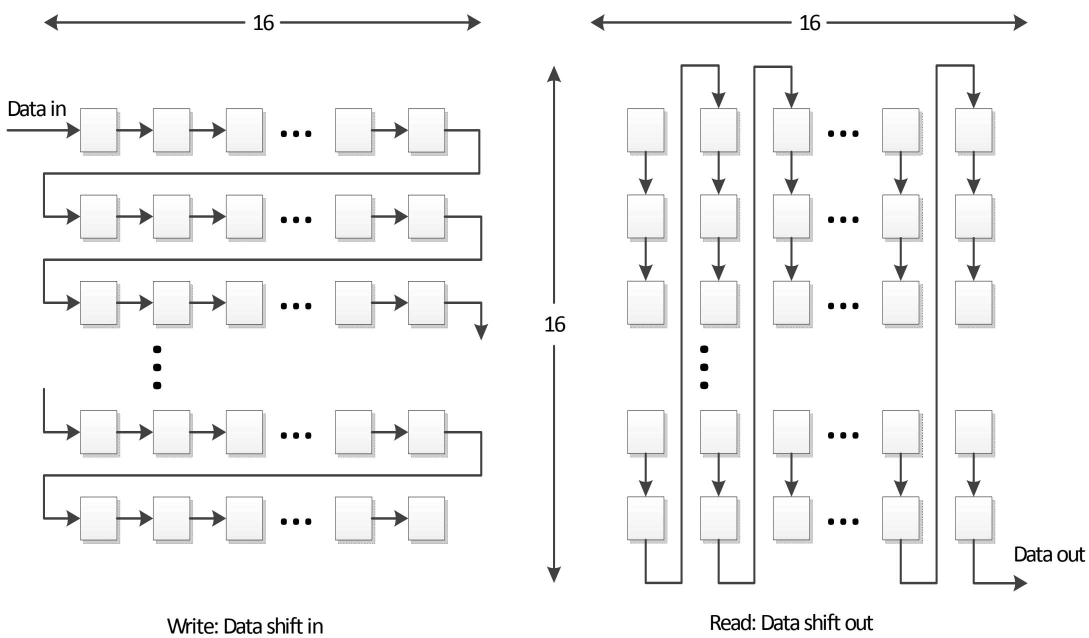

Figure 158—Interleaver for RC PHY

21.5 Modulation

The modulation scheme and data rate shall be configured by TBD.

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.

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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 RC PHY with GMSK modulation.

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

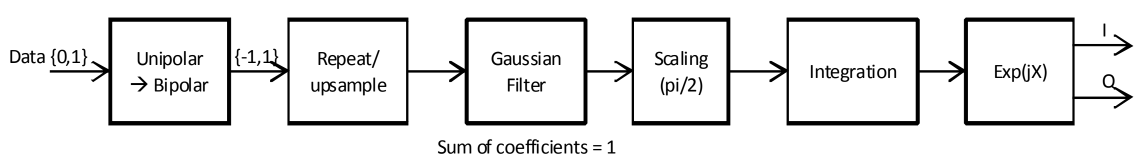

Figure 159—Typical GMSK modulator for RC PHY

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.

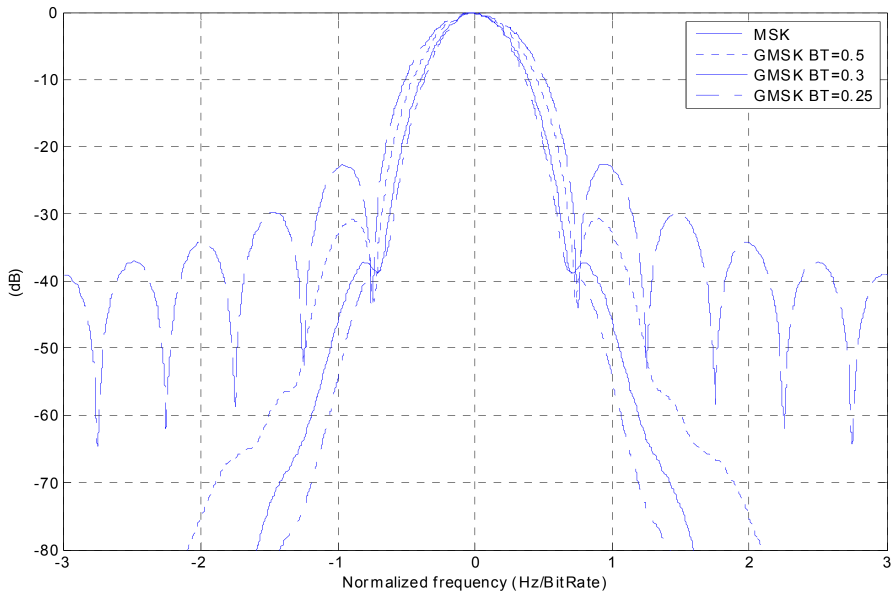

Figure 160—Typical GMSK power spectrum density

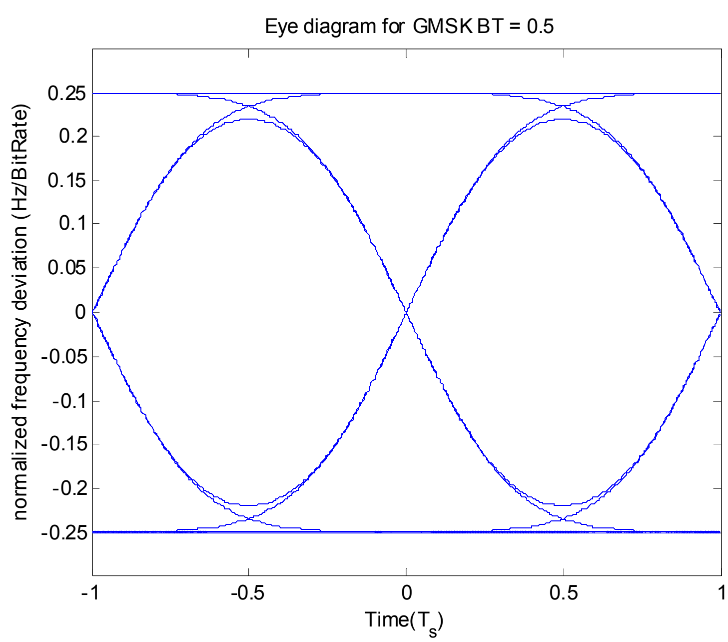

Figure 161—Eye diagram for GMSK with BT=0.5

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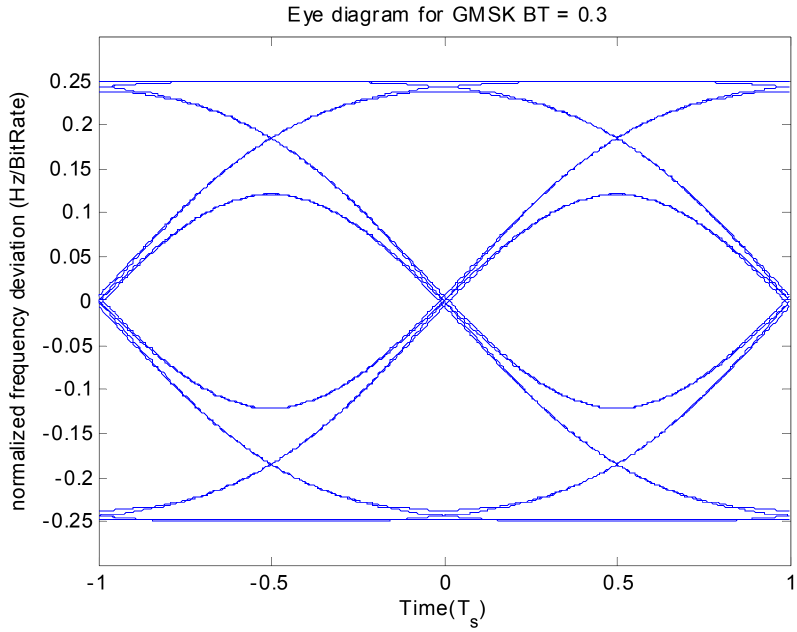

Figure 162—Eye diagram for GMSK with BT=0.3

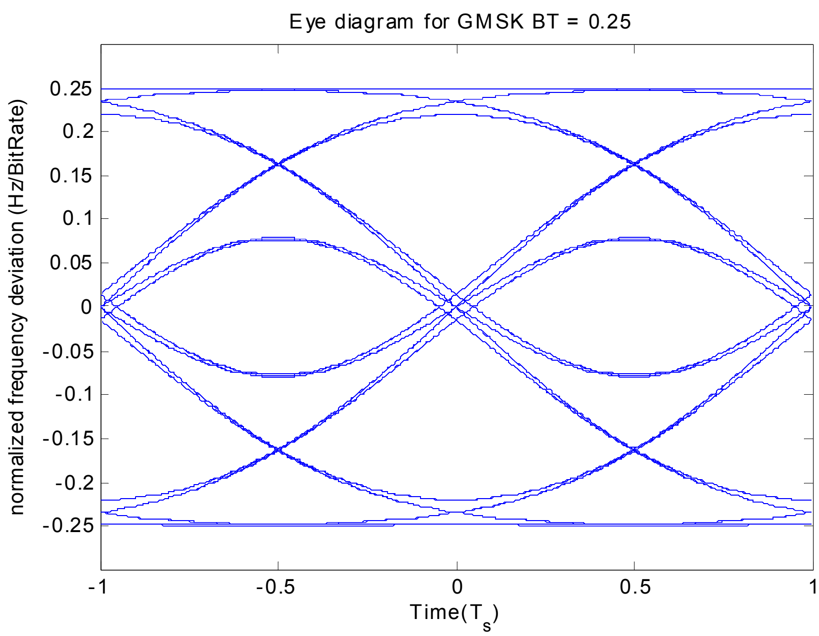

Figure 163—Eye diagram for GMSK with BT=0.25

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 RC PHY with C4FM modulation.

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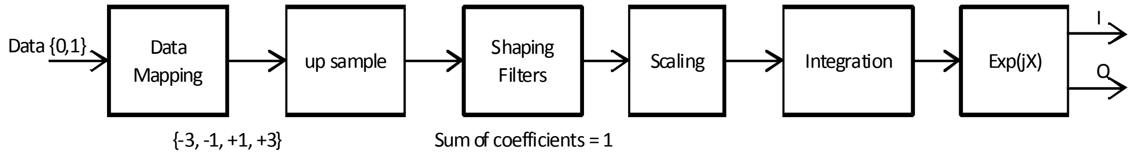

Figure 164—Typical C4FM modulator for RC PHY

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:

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

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 RC PHY

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

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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 RC 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.

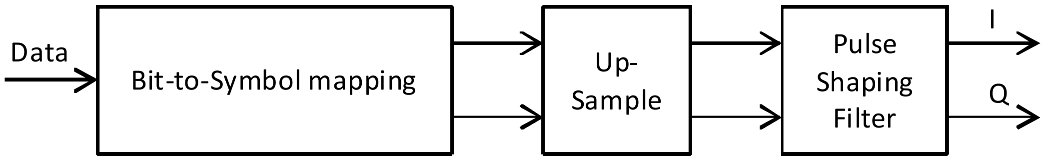

Figure 165—Typical QPSK modulator for RC PHY

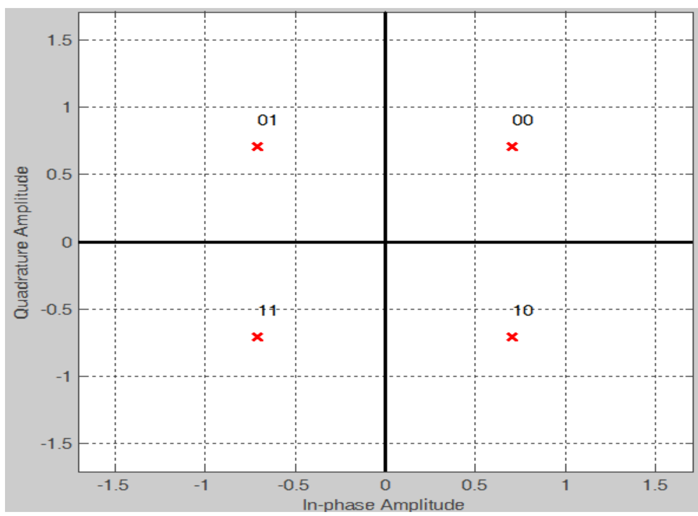

Figure 166—Bit-to-symbol mapping for QPSK (RC PHY)

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 RC 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.

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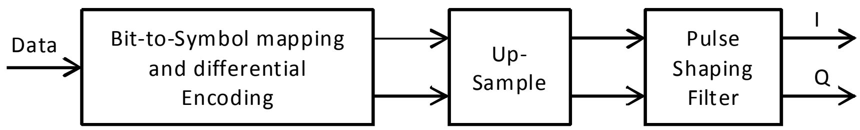

Figure 167—Typical Pi/4 DQPSK modulator for RC PHY

Table 75—Pi/4 DQPSK encoding values for RC 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.

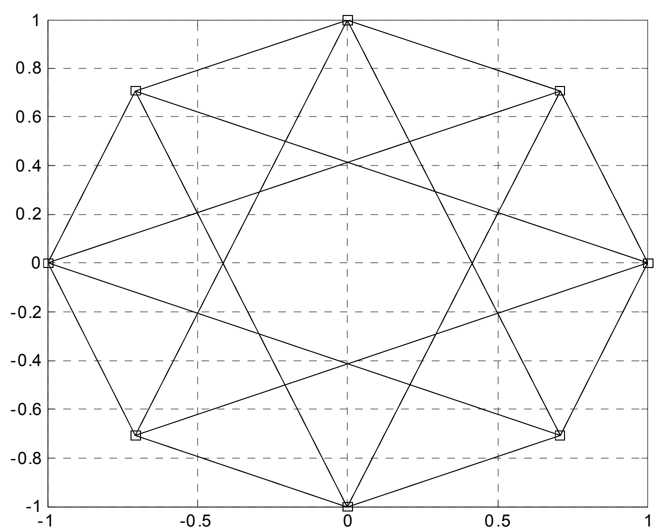

Figure 168—Signal constellation of Pi/4 DQPSK for RC PHY

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21.6 Reference modulator diagram

The functional block diagram in Figure 169 serves as a reference for specifying the RC 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.

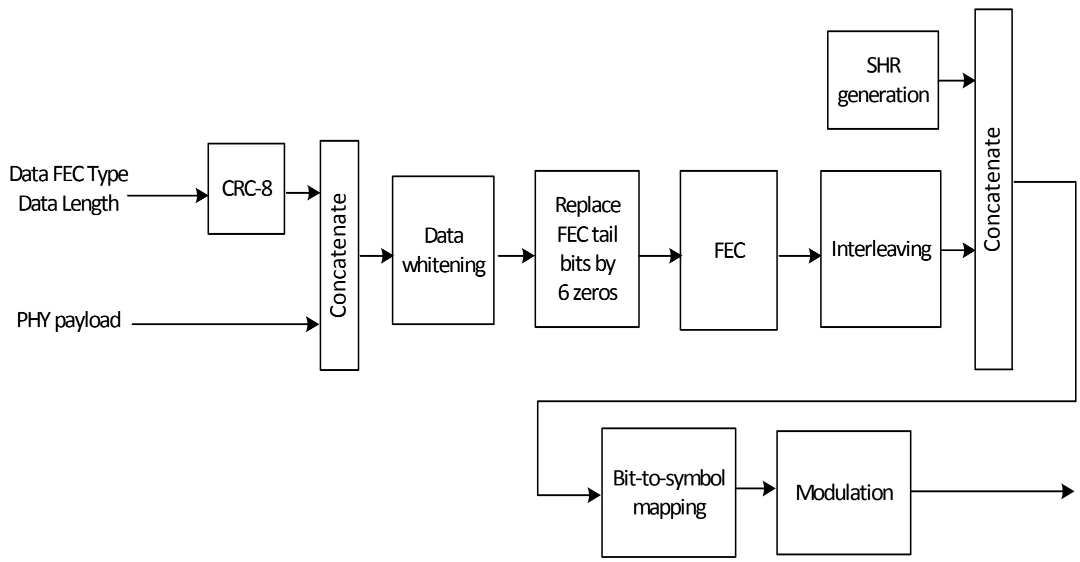

Figure 169—RC PHY reference modulator diagram

21.7 RC 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 RC PHY transmit spectral mask shall conform with local regulations.

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21.7.5 Error vector magnitude

When the RC 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

A transmitter shall be capable of transmitting output power according to Table 76. The maximum transmit power is limited by local regulatory bodies.

Table 76—RC PHY transmit power values

Frequency band (MHz)	Transmit power (dBm)
160.215–161.565	TBD
217–220	TBD
220–222	TBD
450–470	TBD
700	TBD
800	TBD
896–901	TBD
901–902	TBD
902–928	TBD
928–960	TBD
4940–4990	TBD
5725–5850	TBD

21.7.7 Receiver sensitivity

Under the conditions specified in 8.1.7, a compliant device shall be capable of achieving receiver sensitivity according to Table 77 without FEC.

Table 77—RC PHY receiver sensitivity values

Modulation	Receiver sensitivity (dBm)
GMSK 9.6 Kbps	–104 (TBD)
GMSK 19.2 Kbps	–101 (TBD)
C4FM 9.6 Kbps	–108 (TBD)
C4FM 19.2 Kbps	–105 (TBD)
C4FM 38.64Kbps	–102 (TBD)

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Table 77—RC PHY receiver sensitivity values

Modulation	Receiver sensitivity (dBm)
QPSK 16 Kbps	–110 (TBD)
QPSK 32 Kbps	–107 (TBD)
Pi/4 DQPSK 16 Kbps	–108 (TBD)
Pi/4 DQPSK 32 Kbps	–105 (TBD)

21.7.8 Receiver interference rejection

The minimum receiver interference rejection requirements are given in Table 78.

Table 78—Minimum receiver interference rejection requirements for RC PHY

Modulation	Interference frequency offset from desired channel (kHz)
GMSK 9.6 Kbps	±25
GMSK 19.2 Kbps	±50
C4FM 9.6 Kbps	±25
C4FM 19.2 Kbps	±50
C4FM 38.64Kbps	±100
QPSK 16 Kbps	±25
QPSK 32 Kbps	±50
Pi/4 DQPSK 16 Kbps	±25
Pi/4 DQPSK 32 Kbps	±50

The interference rejection shall be 35 dB for all modulation types. The interference rejection shall be measured by setting the strength of the desired signal 6 dB above the modulation dependent sensitivity specified in Table 77. The interference signal shall use the same modulation as the desired signal.

21.7.9 Receiver maximum input level of desired signal

The RC PHY shall have a receiver maximum input level greater than or equal to +10 dBm (TBD) using the measurement defined in 8.2.4.

21.7.10 TX-to-RX turnaround time

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

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

21.7.13 Link quality indicator (LQI)

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

21.7.14 Clear channel assessment (CCA)

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

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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

TBD

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