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Source	David Davenport[1], Neal Seidl[2], Jeremy Moss[3], Maulin Patel[4], Anuj Batra[5], Jin-Meng Ho[5], Srinath Hosur[5], JuneChul Roh[5], Tim Schmidl[5], Okundu Omeni[6], Alan Wong[6] (1) GE Global Research, davenport@research.ge.com, 518-387-5041, 1 Research Circle, Niskayuna, NY, USA (2) GE Healthcare, neal.seidl@med.ge.com, 414-362-3413, 8200 West Tower Avenue, Milwaukee, WI, USA (3) Philips, j.moss@philips.com, +44 1223 427530, 101 Cambridge Science Park, Milton Road, Cambridge UK (4) Philips, maulin.patel@philips.com, 914-945-6156, 345 Scarborough Road, Briarcliff Manor, NY, USA (5) Texas Instruments, {batra@ti.com, 214-480-4220}, {jinmengho@ti.com, 214-480-1994}, {hosur@ti.com, 214-480-4432}, {jroh@ti.com, 214-567-4145}, {schmidl@ti.com, 214-480-4460}, 12500 TI Blvd, Dallas, TX, USA (6) Toumaz Technology, {okundu.omeni@tomuaz.com, +44 1235 438950}, {alan.wong@toumaz.com, +44 1235 438961}, Building 3, 115 Milton Park, Abingdon, Oxfordshire, UK
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MedWiN Physical Layer Proposal

Authors:

David Davenport[1], Neal Seidl[2], Jeremey Moss[3], Maulin Patel[4]
Anuj Batra[5], Jin-Meng Ho[5], Srinath Hosur[5], June Chul Roh[5]
Tim Schmidl[5], Okundu Omeni[6], Alan Wong[6]

(1)   GE Global Research, davenport@research.ge.com, 518-387-5041, 1 Research Circle, Niskayuna, NY, USA

(2)   GE Healthcare, neal.seidl@med.ge.com, 414-362-3413, 8200 West Tower Ave, Milwaukee, WI, USA

(3)   Philips, j.moss@philips.com, +44 1223 427530, 101 Cambridge Science Park, Milton Road, Cambridge, UK

(4)   Philips, maulin.patel@philips.com, +1-914-945-6156, 345 Scarborough Rd, Briarcliff Manor, NY, USA

(5)   Texas Instruments, {batra, jinmengho, hosur, jroh, schmidl}@ti.com, 12500 TI Blvd, Dallas, TX 75243

(6)   Toumaz Technology, {okundu.omeni, alan.wong}@toumaz.com, Bldg 3, 115 Milton Park, Abingdon, Oxfordshire, UK

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1   Acronyms and abbreviations

BCH Code   Bose, Ray-Chaudhuri, Hocquenghem Code

DBPSK   Differential Binary Phase-Shift Keying

DQPSK   Differential Quadrature Phase-Shift Keying

D8PSK   Differential 8-Phase-Shift Keying

EIRP   Equivalent Isotropically Radiated Power

EVM   Error Vector Magnitude

FCS   Frame Check Sequence

HCS   Header Check Sequence

MAC   Media Access Control

PHY   Physical Layer

PLCP   Physical Layer Convergence Protocol

PPDU   Physical Layer Protocol Data Unit

PSDU   Physical Service Data Unit

SIFS   Short Inter-frame Spacing

SRRC   Square-Root Raised Cosine

2   Physical-Layer Convergence Protocol Layer (PLCP)

This clause provides a method for transforming a physical-layer service data unit (PSDU) into a physical-layer protocol data unit (PPDU). During the transmission, the PSDU shall be pre-appended with a physical-layer preamble and a physical-layer header in order to create the PPDU. At the receiver, the physical-layer preamble and physical-layer header serve as aids in the demodulation, decoding and delivery of the PSDU.

2.1   Physical-Layer Protocol Data Unit

Figure 1 shows the format for the PPDU, which is composed of three main components: the PLCP preamble, the PLCP header and the PSDU. The components are listed in the order of transmission. The PLCP preamble is the first component of the PPDU (see Section 2.4). The purpose of the preamble is to aid the receiver in the timing synchronization and carrier-offset recovery.

The PLCP header is the second main component of the PPDU (see Section 2.5). The purpose of this component is to convey the necessary information about the PHY and MAC parameters to aid in decoding of the PSDU at the receiver. The PLCP header can be further decomposed into a RATE field, a LENGTH field, a BURST MODE field, a header check sequence (HCS), BCH parity bits and reserved bits. The BCH parity bits are added in order to improve the robustness of the PLCP header. The PLCP header shall be transmitted using the given header data rate in the operating frequency band.

The PSDU is the last component of the PPDU (see Section 2.6). This component is formed by concatenating the MAC header with the MAC frame body and frame check sequence (FCS). The PSDU is then scrambled and optionally encoded by a BCH code. The PSDU shall be transmitted using any of the available data rates available in the operating frequency band.
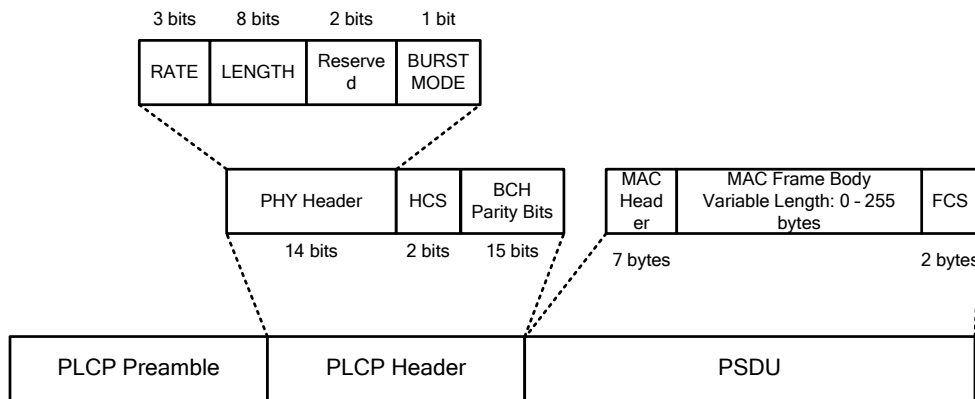
Figure 1 — Standard PPDU structure

When transmitting the packet, the PLCP preamble is sent first, followed by the PLCP header and finally the PSDU. All multiple byte fields shall be transmitted with least significant byte first and each byte shall be transmitted with least significant bit (LSB) first.

A compliant device shall be able to support transmission and reception in one of the following frequency bands: 2400 – 2483.5 MHz, 2360 – 2400 MHz, 402 – 405 MHz, 902 – 928 MHz, 950 – 956 MHz and 863 – 870 MHz.

2.2   Data Rate-dependent Parameters for PLCP Header

Table 1 — Modulation parameters for PLCP Header

Frequency Band (MHz)	Constellation	M	Symbol Rate (ksps)	Pulse Shape	Code Rate (k/n)	Spreading Factor (S)	Information Data Rate (kbps)
2360 – 2483.5	π/2-DBPSK	2	631.58	SRRC	16/31	4	81.5
402 – 405	π/2-DBPSK	2	176.47	SRRC	16/31	1	91.1
902 – 928	π/2-DBPSK	2	315.79	SRRC	16/31	2	81.5
950 – 956	π/2-DBPSK	2	250.00	SRRC	16/31	1	129.0
863 – 870	π/2-DBPSK	2	125.00	SRRC	16/31	1	64.5

2.3   Data Rate-dependent Parameters for PSDU

A compliant device shall be able to support transmission and reception in one of the following frequency bands. Support for π/2-DBPSK and π/4-DQPSK is mandatory, while support for π/8-D8PSK is optional.

Table 2 — Modulation parameters for PSDU in 2400 MHz frequency band

Frequency Band (MHz)	Constellation	M	Symbol Rate (ksps)	Pulse Shape	Code Rate (k/n)	Spreading Factor (S)	Information Data Rate (kbps)
2360 – 2483.5	π/2-DBPSK	2	631.58	SRRC	51/63	4	127.8
	π/2-DBPSK	2	631.58	SRRC	51/63	2	255.6
	π/2-DBPSK	2	631.58	SRRC	51/63	1	511.3
	π/4-DQPSK	4	631.58	SRRC	51/63	1	1022.6

Table 3 — Modulation parameters for PSDU in 400 MHz frequency band

Frequency Band (MHz)	Constellation	M	Symbol Rate (ksps)	Pulse Shape	Code Rate (k/n)	Spreading Factor (S)	Information Data Rate (kbps)
402 – 405	π/2-DBPSK	2	176.47	SRRC	45/63	1	126.1
	π/4-DQPSK	4	176.47	SRRC	45/63	1	252.1
	π/4-DQPSK	4	176.47	SRRC	1/1	1	352.9
	π/8-D8PSK	8	176.47	SRRC	51/63	1	428.6

Table 4 — Modulation parameters for PSDU in 900 MHz frequency band

Frequency Band (MHz)	Constellation	M	Symbol Rate (ksps)	Pulse Shape	Code Rate (k/n)	Spreading Factor (S)	Information Data Rate (kbps)
902 – 928	π/2-DBPSK	2	315.79	SRRC	51/63	2	127.8
	π/2-DBPSK	2	315.79	SRRC	51/63	1	255.6
	π/4-DQPSK	4	315.79	SRRC	51/63	1	511.3
	π/8-D8PSK	8	315.79	SRRC	51/63	1	766.9
950 – 956	π/2-DBPSK	2	250.00	SRRC	39/63	1	154.8
	π/2-DQPSK	2	250.00	SRRC	1/1	1	250.0
	π/4-DQPSK	4	250.00	SRRC	1/1	1	500.0
	π/8-D8PSK	8	250.00	SRRC	51/63	1	607.1
863 – 870	π/2-DBPSK	2	125.00	SRRC	51/63	1	101.2
	π/4-DQPSK	4	125.00	SRRC	45/63	1	178.6
	π/4-DQPSK	4	125.00	SRRC	1/1	1	250.0
	π/8-D8PSK	8	125.00	SRRC	51/63	1	303.6

2.4   PLCP Preamble

A preamble shall be added prior to the PLCP header in order to aid the receiver in packet detection, timing synchronization and carrier-offset recovery. Two unique preambles are defined in order to mitigate false alarms due to networks operating on adjacent channels. The mapping between channel number and preamble is defined in Section 3.1.3. Each preamble is constructed by concatenating a length-63 m-sequence with a 010101010 sequence. The former sequence can be used to implement packet detection, coarse-timing synchronization and carrier-offset recovery, while the latter sequence can be used to implement fine-timing synchronization.

The two preamble sequences are defined in Table 5 and Table 6. The preambles will be transmitted at the symbol rate for the desired band of operation and will be encoded using $\pi/2$-DBPSK.

Table 5 — Preamble Sequence #1

Bit	Bit Value	Bit	Bit Value	Bit	Bit Value	Bit	Bit Value
b_0	0	B_{18}	0	b_{36}	1	b_{54}	0
b_1	1	B_{19}	1	b_{37}	0	b_{55}	0
b_2	0	b_{20}	0	b_{38}	0	b_{56}	0
b_3	1	b_{21}	0	b_{39}	1	b_{57}	1
b_4	0	b_{22}	1	b_{40}	0	b_{58}	1
b_5	1	b_{23}	0	b_{41}	1	b_{59}	1
b_6	1	b_{24}	0	b_{42}	0	b_{60}	1
b_7	0	b_{25}	1	b_{43}	0	b_{61}	1
b_8	0	b_{26}	1	b_{44}	0	b_{62}	1
b_9	1	b_{27}	1	b_{45}	1	b_{63}	0
b_{10}	1	b_{28}	0	b_{46}	1	b_{64}	1
b_{11}	0	b_{29}	0	b_{47}	0	b_{65}	0
b_{12}	1	b_{30}	0	b_{48}	0	b_{66}	1
b_{13}	1	b_{31}	1	b_{49}	0	b_{67}	0
b_{14}	1	b_{32}	0	b_{50}	0	b_{68}	1
b_{15}	0	b_{33}	1	b_{51}	1	b_{69}	0
b_{16}	1	b_{34}	1	b_{52}	0	b_{70}	1
b_{17}	1	b_{35}	1	b_{53}	0	b_{71}	0

Table 6 — Preamble Sequence #2

Bit	Bit Value	Bit	Bit Value	Bit	Bit Value	Bit	Bit Value
b_0	0	B_{18}	0	b_{36}	0	b_{54}	0
b_1	1	B_{19}	1	b_{37}	0	b_{55}	1
b_2	1	b_{20}	0	b_{38}	1	b_{56}	0
b_3	0	b_{21}	1	b_{39}	1	b_{57}	1
b_4	1	b_{22}	0	b_{40}	0	b_{58}	1
b_5	0	b_{23}	1	b_{41}	1	b_{59}	1
b_6	0	b_{24}	0	b_{42}	1	b_{60}	1
b_7	0	b_{25}	0	b_{43}	1	b_{61}	1
b_8	1	b_{26}	1	b_{44}	0	b_{62}	1
b_9	0	b_{27}	0	b_{45}	0	b_{63}	0
b_{10}	0	b_{28}	0	b_{46}	1	b_{64}	1
b_{11}	0	b_{29}	1	b_{47}	1	b_{65}	0
b_{12}	0	b_{30}	1	b_{48}	0	b_{66}	1
b_{13}	1	b_{31}	1	b_{49}	0	b_{67}	0
b_{14}	0	b_{32}	1	b_{50}	0	b_{68}	1
b_{15}	1	b_{33}	0	b_{51}	1	b_{69}	0
b_{16}	1	b_{34}	0	b_{52}	1	b_{70}	1
b_{17}	0	b_{35}	0	b_{53}	1	b_{71}	0

2.5   PLCP Header

A PLCP header shall be added after the PLCP preamble to convey information about the PHY and MAC parameters that is needed at receiver in order to decode the PSDU. The BCH encoded PLCP header shall be formed as shown in Figure 2:

1.   Format the PHY header as shown in Figure 2 based on information provided by the MAC

2.   Calculate the 2-bit HCS value over the PHY header

3. Apply a BCH (31,16) code to the concatenation of the PHY header (14 bits) and HCS (2 bits)

The resulting encoded bits are modulated using the appropriate parameters specified in Table 1 for the desired frequency band of operation.
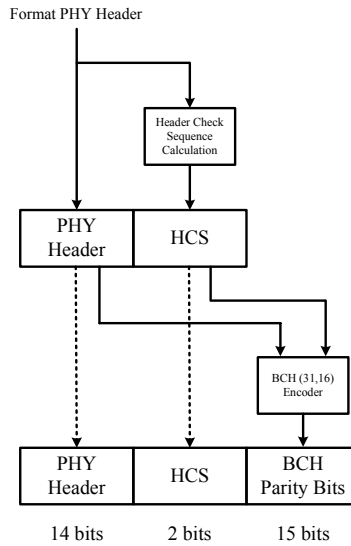

Figure 2 — Block diagram of PLCP header construction

2.5.1 PHY Header

The PHY header contains information about the data rate of the MAC frame body, the length of the MAC frame body (which does not include the MAC header or the FCS) and information about the next packet – whether it is being sent in a burst mode.

The PHY header field shall be composed of 14 bits, numbered from 0 to 13 as illustrated in Figure 3. Bits 0-2 shall encode the RATE field, which conveys the information about the type of modulation, the symbol rate, frequency deviation or pulse shape, the coding rate, and the spreading factor used to transmit the PSDU. Bits 3-10 shall encode the LENGTH field, with the least-significant bit being transmitted first. Bit 13 shall encode whether or not the packet is being transmitted in the burst (streaming) mode. All other bits which are not defined in this Clause shall be understood to be reserved for future use and shall be set to zero.
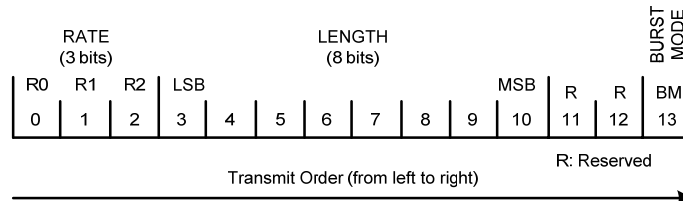
Figure 3 — PHY Header bit assignment

2.5.1.1   Data Rate (RATE)

Depending on the data rate (RATE), bits R0–R2 shall be set according to the values in Table 7.

Table 7 — Rate-dependent parameters

R0 – R2	Data Rate (kbps) 2360-2483.5 MHz	Data Rate (kbps) 402-405 MHz	Data Rate (kbps) 902-928 MHz	Data Rate (kbps) 950-956 MHz	Data Rate (kbps) 863-870 MHz
000	127.8	126.1	127.8	154.8	101.2
001	255.6	252.1	255.6	250.0	178.6
010	511.3	352.9	511.3	500.0	250.0
011	1022.6	428.6	766.9	607.1	303.6
100	Reserved	Reserved	Reserved	Reserved	Reserved
101	Reserved	Reserved	Reserved	Reserved	Reserved
110	Reserved	Reserved	Reserved	Reserved	Reserved
111	Reserved	Reserved	Reserved	Reserved	Reserved

2.5.1.2   PLCP Length Field (LENGTH)

The PLCP length field shall be an unsigned 8-bit integer that indicates the number of un-coded information bytes in the MAC frame body (which does not include the MAC header or the FCS).

2.5.1.3   Burst Mode Field (BM)

The MAC shall set the burst mode (BM) bit, as defined in Table 8, to indicate whether the next packet is part of a packet "burst", i.e. burst mode transmission. In burst mode, the inter-frame spacing shall be equal to a pSIFS (see Section 3.2.4).

Table 8 — Burst Mode field

Burst Mode (BM) bit	Next Packet Status
0	Next packet *is not* part of burst
1	Next packet *is* part of burst

2.5.2   BCH Encoder for PLCP Header

The PLCP header shall use a systematic BCH (31, 16, t = 3) code to improve the robustness of the PLCP header. The generator polynomial for this BCH code is:

$$g(x) = 1 + x + x^2 + x^3 + x^5 + x^7 + x^8 + x^9 + x^{10} + x^{11} + x^{15}. \tag{1}$$

The parity bits are determined by computing the remainder polynomial $r(x)$:

$$r(x) = \sum_{i=0}^{14} r_i x^i = x^{15} m(x) \bmod g(x), \tag{2}$$

where $m(x)$ is the message polynomial:

$$m(x) = \sum_{i=0}^{15} m_i x^i, \tag{3}$$

and $r_i, i = 0,\ldots,14$ and $m_i, i = 0,\ldots,15$ are elements of $GF(2)$. The message polynomial $m(x)$ is created as follows: m_{15} is the first bit of the PHY header, m_2 is the last bit of the PHY header, m_1 is the first bit of the HCS and m_0 is the last bit of the HCS. The order of the parity bits is as follows: r_{14} is the first parity bit transmitted, r_{13} is the second parity bit transmitted, and r_0 is the last parity bit transmitted.

A shift-register implementation of the BCH encoding process is shown in Figure 4, with the additions over $GF(2)$. After m_0 has been inserted into the shift register, the switch shall be moved from the message polynomial input connection to the shift register output connection (right-to-left).
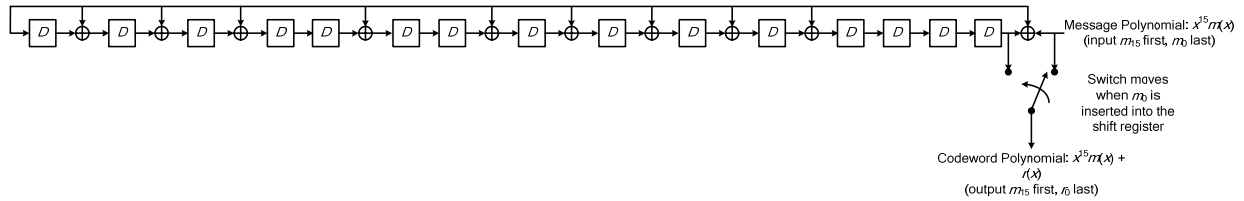
Figure 4 — Shift register implementation of a systematic BCH (31, 16) encoder

2.5.3   Header Check Sequence

The PHY header shall be protected with a 2-bit (CRC-2) header check sequence (HCS). The HCS shall be the ones complement of the remainder generated by the modulo-2 division of the PHY header by the polynomial: $1 + x + x^2$. The HCS bits shall be processed in the transmit order. A schematic of the processing order is shown in Figure 5. The registers shall be initialized to all ones.

Preset
Registers
to ONES

Serial
Data
Input → CRC-2 → Serial
Data
Output

Serial
Data
Input → ⊕ ← D ← ⊕ ← D ←
MSB   LSB

ONES
Complement → Serial
Data
Output
(MSB First)

Figure 5 — Block diagram of a CRC-2 implementation

2.6 PSDU

The PSDU is the last major component of the PPDU and shall be constructed as shown in Figure 6.

1. Form the non-scrambled PSDU by pre-pending the 7-byte MAC header to the MAC frame body and appending a 2-byte FCS to the result.
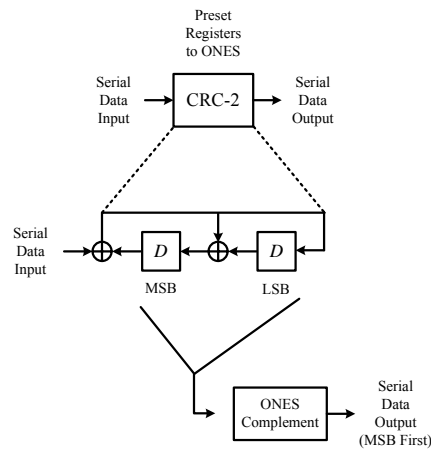
2. The resulting PSDU is scrambled according to Section 2.6.1.

3. If the code rate $(k/n) < 1$, the scrambled output is:

   a. Divided into blocks of messages, where each message may contain shortened bits, according to Section 2.6.2.1;

   b. The resulting messages are then encoded into codewords using the appropriate BCH encoder to achieve the desired code rate: a BCH (63, 39), a BCH (63, 45) or a BCH (63, 51) code, according to Sections 2.6.2.2 - 2.6.2.4;

   c. Finally, the shortened bits are removed from each of the codewords.

4. Pad bits are then added in order to ensure alignment on a symbol boundary according to Section 2.6.3.

5. If the spreading factor is 2 or 4, the resulting un-coded or coded bits are spread using a repetition code, according to Section 2.6.4, and then interleaved using a bit interleaver defined in Section 2.6.5.

6. Finally, the resulting un-coded or coded and potentially spread and interleaved bit steam is then mapped onto the appropriate constellation (see Section 2.6.6), which is determined by the data rate and frequency band of operation (see Table 2 through Table 4).
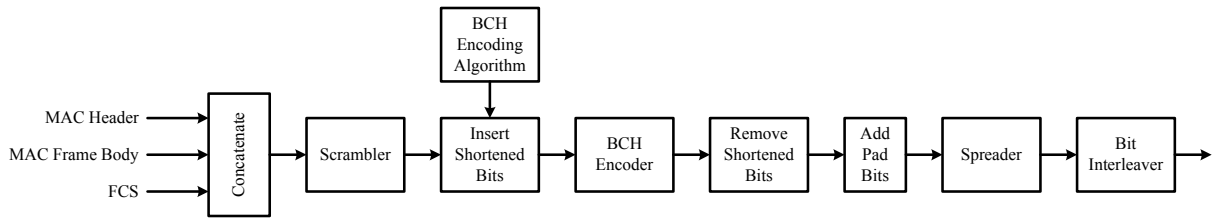
Figure 6 — Block diagram of PSDU construction

2.6.1 Data Scrambler

The polynomial $G(x) = 1 + x^{-4} + x^{-7}$ shall be used to scramble the PSDU, i.e., the concatenation of the MAC header, MAC frame body and FCS. The feed-through configuration of the scrambler and descrambler is self-synchronizing, which requires no prior knowledge of the transmitter initialization of the scrambler for receive processing. Figure 7 and Figure 8 show typical implementations of the data scrambler and descrambler, but other implementations are possible.
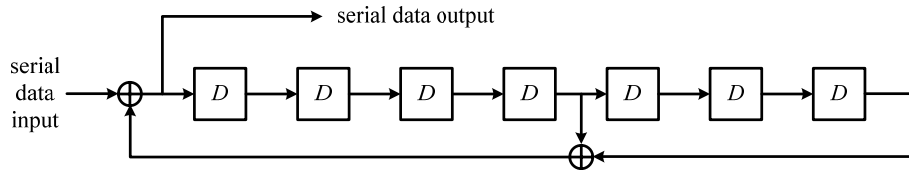
Figure 7 — Block diagram of data scrambler
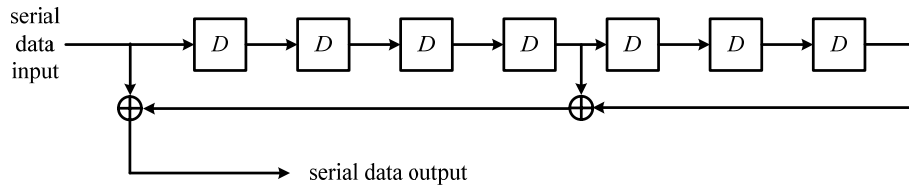
Figure 8 — Block diagram of data de-scrambler

2.6.2 BCH Encoder for PSDU

The following coding rates: 39/63, 45/63 and 51/53, shall be supported by the systematic BCH encoders. The information bits shall be encoded using BCH encoding process defined in Section 2.6.2.1. The definitions for the three systematic BCH encoders shall be defined in Sections 2.6.2.2 – 2.6.2.4.

2.6.2.1 BCH Encoding Process

The scrambled PSDU shall be encoded using the following procedure:

1. Compute the number of bits in the PSDU N_{PSDU}:

$$N_{PSDU} = (N_{MACheader} + N_{MACFrameBody} + N_{FCS}) \times 8 \qquad (4)$$

where $N_{MACheader}$ is the number of bytes in the MAC header, $N_{MACFrameBody}$ is the number of bytes in the MAC frame body and N_{FCS} is the number of bytes in the FCS.

2. Calculate the number of BCH codeword N_{CW}:

$$N_{CW} = \left\lceil \frac{N_{PSDU}}{k} \right\rceil \qquad (5)$$

where k is the number of message bits for the selected BCH code.

3. Compute the number of shortening bits, $N_{shorten}$, to be padded to the N_{PSDU} data bits before encoding as follows:

$$N_{shorten} = N_{CW} \times k - N_{PSDU} \qquad (6)$$

4. The shortening bits shall be equally distributed over all N_{CW} codewords with the first $rem(N_{shorten}, N_{CW})$ codewords being shortened one bit more than the remaining codewords. Let

$$N_{spcw} = \left\lfloor \frac{N_{shorten}}{N_{CW}} \right\rfloor. \qquad (7)$$

Thus, the first $rem(N_{shorten}, N_{CW})$ codewords will have $N_{spcw} + 1$ shortened bits (message bits that are set to 0), while the remaining codewords will have N_{spcw} shortened bits. After encoding, the shortened bits shall be discard prior to transmission, i.e., the shortened bits are never transmitted on-air.

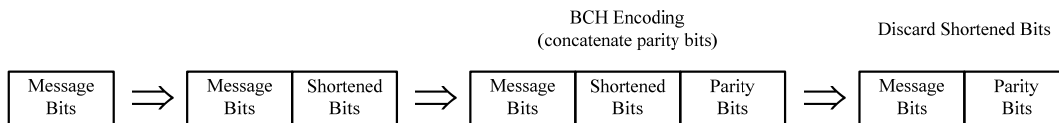The BCH encoding process is illustrated in Figure 9 for a single codeword.

Figure 9 — BCH encoding process for a single codeword

2.6.2.2   BCH (63, 39) Encoder

The generator polynomial for a systematic BCH (63, 39, $t = 4$) code is given by:

$$g(x) = 1 + x + x^2 + x^4 + x^5 + x^6 + x^8 + x^9 + x^{10} + x^{13} + x^{16} + x^{17} + x^{19} + x^{20} + x^{22} + x^{23} + x^{24}. \qquad (8)$$

The parity bits are determined by computing the remainder polynomial $r(x)$:

$$r(x) = \sum_{i=0}^{23} r_i x^i = x^{24} m(x) \bmod g(x) ,$$ (9)

where $m(x)$ is the message polynomial:

$$m(x) = \sum_{i=0}^{38} m_i x^i ,$$ (10)

and $r_i, i = 0,\ldots,23$ and $m_i, i = 0,\ldots,38$ are elements of $GF(2)$. The message polynomial $m(x)$ is created as follows: m_{38} is the first bit of the message and m_0 is the last bit of the message, which maybe a shortened bit. The order of the parity bits is as follows: r_{23} is the first parity bit transmitted, r_{22} is the second parity bit transmitted, and r_0 is the last parity bit transmitted.

2.6.2.3   BCH (63, 45) Encoder

The generator polynomial for a systematic BCH (63, 45, t = 3) code is given by:

$$g(x) = 1 + x + x^2 + x^3 + x^6 + x^7 + x^9 + x^{15} + x^{16} + x^{17} + x^{18} .$$ (11)

The parity bits are determined by computing the remainder polynomial $r(x)$:

$$r(x) = \sum_{i=0}^{17} r_i x^i = x^{18} m(x) \bmod g(x) ,$$ (12)

where $m(x)$ is the message polynomial:

$$m(x) = \sum_{i=0}^{44} m_i x^i ,$$ (13)

and $r_i, i = 0,\ldots,17$ and $m_i, i = 0,\ldots,44$ are elements of $GF(2)$. The message polynomial $m(x)$ is created as follows: m_{44} is the first bit of the message and m_0 is the last bit of the message, which maybe a shortened bit. The order of the parity bits is as follows: r_{17} is the first parity bit transmitted, r_{16} is the second parity bit transmitted, and r_0 is the last parity bit transmitted.

2.6.2.4   BCH (63, 51) Encoder

The generator polynomial for a systematic BCH (63, 51, t = 2) code is given by:

$$g(x) = 1 + x^3 + x^4 + x^5 + x^8 + x^{10} + x^{12} .$$ (14)

The parity bits are determined by computing the remainder polynomial $r(x)$:

$$r(x) = \sum_{i=0}^{11} r_i x^i = x^{12} m(x) \bmod g(x) , \tag{15}$$

where $m(x)$ is the message polynomial:

$$m(x) = \sum_{i=0}^{50} m_i x^i , \tag{16}$$

and $r_i, i = 0,\dots,11$ and $m_i, i = 0,\dots,50$ are elements of $GF(2)$. The message polynomial $m(x)$ is created as follows: m_{50} is the first bit of the message and m_0 is the last bit of the message, which maybe a shortened bit. The order of the parity bits is as follows: r_{11} is the first parity bit transmitted, r_{10} is the second parity bit transmitted, and r_0 is the last parity bit transmitted.

2.6.3 Pad Bits

Pad bits shall be appended after the BCH encoder to ensure that the bit stream aligns on a symbol boundary. The number of pad bits, N_{pad} , that shall be inserted is a function of the number of PSDU bits N_{PSDU} , the number of codewords N_{CW} , the number of parity bits $(n-k)$, and the modulation constellation size M :

$$N_{pad} = \log_2(M) \times \left\lceil \frac{N_{PSDU} + N_{CW} \times (n-k)}{\log_2(M)} \right\rceil - \left[N_{PSDU} + N_{CW} \times (n-k) \right]. \tag{17}$$

The pad bits shall be appended to scrambled and encoded PSDU and all of the appended pad bits shall be set to 0.

2.6.4 Spreading

For a spreading factor of 2, each input bit is repeated two times (see illustration in Figure 10a). For a spreading factor of 4, each input bit is repeated four times (see illustration in Figure 10b).
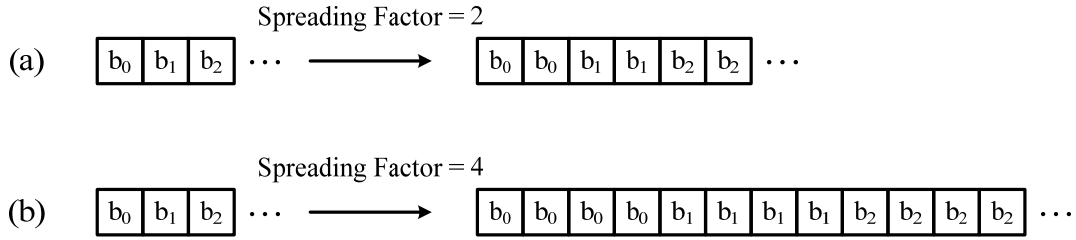
Figure 10 — Spreading scheme

2.6.5   Bit Interleaver

The output of the spreader shall be interleaved prior to modulation to provide robustness against error propagation. The exact structure of the bit interleaver depends on the number of un-coded or coded bits that will be transmitted on-air, which is given by:

$$N_{total} = N_{PSDU} + N_{CW} \times (n - k) + N_{pad} \,. \tag{18}$$

If $rem(N_{total}, 2) = 0$, the bit interleaving operation is performed by first grouping the spread bits into blocks of $2S$ bits, where S is the spreading factor, and then using a block interleaver of size $S \times 2$ to permute the bits. Let the sequences $a(i)$ and $b(i)$, where $i = 0, 1, \ldots, 2S - 1$, represent the input and output bits of the $S \times 3$ bit interleaver, respectively. The output of the $S \times 2$ bit interleaver is given by the following relationship:

$$b(i) = a\left[S \times rem(i, 2) + \left\lfloor \frac{i}{2} \right\rfloor \right] \quad i = 0, 1, \ldots, 2S - 1. \tag{19}$$

If $rem(N_{total}, 2) = 1$, the bit interleaving operation is performed by grouping the first $3S$ spread bits into a single block and then using a block interleaver of size $S \times 3$ to permute the bits within that single block. Let the sequences $a(i)$ and $b(i)$, where $i = 0, 1, \ldots, 3S - 1$, represent the input and output bits of the $S \times 3$ bit interleaver, respectively. The output of the $S \times 3$ bit interleaver is given by the following relationship:

$$b(i) = a\left[S \times rem(i, 3) + \left\lfloor \frac{i}{3} \right\rfloor \right] \quad i = 0, 1, \ldots, 3S - 1. \tag{20}$$

The remaining spread bits are then grouped into blocks of $2S$ bits and interleaved using the block interleaver of size $S \times 2$ shown in (19).

2.6.6   Constellation Mapping

The un-coded or coded, potentially spreading and interleaved bit stream shall be mapped onto one of three rotated and differentially-encoded constellations: π/2-DBPSK, π/4-DQPSK, or π/8-D8PSK. The encoded information is

carried in the phase transitions between symbols. For the PLCP header to PSDU transmission, the phase change is relative to the last symbol for the PLCP header.

The binary bit stream $b(n), n = 0,1,\ldots,N-1$ shall be mapped onto a corresponding complex-values sequence $S(k), k = 0,1,\ldots,\left(N/\log_2(M)\right)-1$ as follows:

$$S(k) = S(k-1)\exp(j\varphi_k) \quad k = 1,2,\ldots,\left(N/\log_2(M)\right)-1. \tag{21}$$

where $S(0) = \exp(j\pi/M)$ and the relationship between the bit stream $b(n)$ and the phase change φ_k is given in Table 9 through Table 11 for π/2-DBPSK, π/4-DQPSK, or π/8-D8PSK, respectively.

Table 9 — π/2-DBPSK Mapping

$b(n)$	φ_k
0	π/2
1	3π/2

Table 10 — π/4-DQPSK Mapping

$b(2n)$	$b(2n+1)$	φ_k
0	0	π/4
0	1	3π/4
1	0	7π/4
1	1	5π/4

Table 11 — π/8-D8PSK Mapping

b(2n)	b(2n+2)	b(2n+2)	φk
0	0	0	π/8
0	0	1	3π/8
0	1	0	7π/8
0	1	1	5π/8
1	0	0	15π/8
1	0	1	13π/8
1	1	0	9π/8
1	1	1	11π/8

3   General Requirements

3.1   Operating Frequencies

3.1.1   Operating Frequency Bands

A compliant device shall be able to support transmissions and reception in one of the following frequency bands:

1.   2400 – 2483.5 MHz

2.   2360 – 2400 MHz

3.   402 – 405 MHz

4.   902 – 928 MHz

5.   950 – 956 MHz

6.   863 – 870 MHz

3.1.2   Channel Numbering

The relationship between center frequency, f_c, and channel number, n_c, is shown in Table 12.

Table 12 — Relationship between Center Frequency and Channel Number

Frequency Band (MHz)	Relationship between f_c and n_c
2400 – 2483.5	$f_c = 2402.00 + 1.00 \times n_c$ (MHz), $n_c = 0, \ldots, 78$
2360 – 2400	$f_c = 2362.00 + 1.00 \times n_c$ (MHz), $n_c = 0, \ldots, 37$
402 – 405	$f_c = 402.15 + 0.30 \times n_c$ (MHz), $n_c = 0, \ldots, 9$
902 – 928	$f_c = 903.50 + 0.50 \times n_c$ (MHz), $n_c = 0, \ldots, 47$
950 – 956	$f_c = 951.10 + 0.40 \times n_c$ (MHz), $n_c = 0, \ldots, 11$
863 – 870	$f_c = 865.60 + 0.20 \times g(n_c)$ (MHz), $n_c = 0, \ldots, 14$

The mapping function $g(n_c)$ used in the 863 – 870 MHz frequency band is defined as follows:

$$g(n_c) = \begin{cases} n_c & 0 \leq n_c \leq 9 \\ n_c + 3 & 10 \leq n_c \leq 11 \\ n_c + 4 & 12 \leq n_c \leq 13 \\ n_c + 7 & n_c = 14 \end{cases}, \tag{22}$$

3.1.3   Preamble Sequence Assignment

The relationship between channel number, n_c, and preamble sequence used in the PLCP preamble is shown in Table 13.

Table 13 — Relationship between Channel Number and Preamble

Preamble Sequence	Relationship between preamble sequence and n_c
1	$rem(n_c,2) = 0$
2	$rem(n_c,2) = 1$

3.2   PHY Layer Timing

The values for the PHY layer timing parameters are defined in Table 14.

Table 14 — Physical layer timing parameters

PHY Parameter	Value
pSIFS	20 μs
pCCATime	63 preamble symbols
pChannelSwitchTime	50 μs

3.2.1   Inter-frame Spacing

The inter-frame spacing parameters are given in Table 15.

Table 15 — Inter-frame spacing parameters

MAC Parameter	Value
SIFS	pSIFS

3.2.2   Receive-to-Transmit Turnaround Time

The RX-to-TX turnaround time shall not be greater than pSIFS. This turnaround time shall be measured at the air interface. The time elapsed from the last received symbol, to the first transmitted symbol of the PLCP preamble for the next frame shall not be greater than pSIFS.

3.2.3   Transmit-to-Receive Turnaround Time

The TX-to-RX turnaround time shall not be greater than pSIFS. This turnaround time shall be measured at the air interface. The time elapsed from the last transmitted symbol until the receiver is ready to begin the reception of the next PHY frame shall not be greater than pSIFS.

3.2.4 Time between Successive Transmissions

For burst mode transmissions, the inter-frame spacing between uninterrupted successive transmissions by a device shall be fixed to exactly pSIFS. The inter-frame spacing time shall be measured at the air interface. The time elapsed from the leading edge of the last transmitted symbol to the leading edge of the first transmitted symbol of the PLCP preamble for the following packet shall be fixed to exactly pSIFS.

3.2.5 Center Frequency Switch Time

The center frequency switch time is defined as the interval from when the PHY transmits or receives the last valid symbol on one center frequency until it is ready to transmit or receive the next symbol on a different center frequency. The center frequency switch time shall not exceed pChannelSwitchTime.

4   Transmitter Specifications

4.1   Transmit PSD Mask

The transmitted spectral mask shall be less than -20 dBr (dB relative to the maximum spectral density of the signal) for $|f - f_c| \geq f_{BW}/2$, where f_c is channel center frequency and f_{BW} is the channel bandwidth and is a function of the frequency band of operation and is defined in Table 16.

Table 16 — Channel bandwidth as a function of the frequency band of operation

Frequency (MHz)	f_{BW}
2360 – 2483.5	1 MHz
402 – 405	300 kHz
902 – 928	500 kHz
950 – 956	400 kHz
863 – 870	200 kHz

The transmitted spectral density also shall comply with all regulations defined by local regulatory bodies.

4.2   Transmit Center Frequency Tolerance

The transmitted center frequency tolerance shall be ±20 ppm maximum.

4.3   Symbol Clock Frequency Tolerance

The symbol clock frequency tolerance shall be ±20 ppm maximum.

4.4   Clock Synchronization

The transmit center frequencies and the symbol clock frequency shall be derived from the same reference oscillator.

4.5   Transmit Power

A transmitter shall be capable of transmitting at least –10 dBm EIRP in all frequency bands, except for 402 – 405 MHz, where a transmitter shall be capable of transmitting at most -16 dBm EIRP. 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.

4.6   Transmitter Constellation Error

The modulation accuracy of the transmitter is determined via an error-vector magnitude (EVM) measurement, which is calculated over N baud-spaced received complex values $\left(\hat{I}_k, \hat{Q}_k\right)$. A decision is made for each received complex value. The ideal position of the chosen symbol is represented by the vector $\left(I_k, Q_k\right)$. The error vector $\left(\delta I_k, \delta Q_k\right)$ is defined as the distance from the ideal position to the actual position of the received complex values, i.e., $\left(\hat{I}_k, \hat{Q}_k\right) = \left(I_k, Q_k\right) + \left(\delta I_k, \delta Q_k\right)$.

The EVM is defined as shown in the equation below:

$$EVM = \sqrt{\frac{\frac{1}{N}\sum_{k=1}^{N}\left(\delta I_k^2 + \delta Q_k^2\right)}{S^2}} \times 100\% \, , \tag{23}$$

where S is the magnitude of the vector to the ideal constellation point. A transmitter shall have EVM values less than or equal to those listed in Table 17 when measure for N = TBD symbols. The EVM shall be measured on baseband I and Q samples after the received signal is passed through a reference receiver, which shall perform the following operations: carrier-frequency offset estimation and symbol timing recovery while making the measurements.

Table 17 — Permissible EVM numbers as a function of constellation size

Constellation	EVM Error
π/2-DBPSK	TBD %
π /4-DQPSK	TBD %
π /8-D8PSK	TBD %

5   Receiver Specifications

5.1   Receiver Sensitivity

For a packet error rate (PER) of less than 10% with a PSDU of 255 bytes, the minimum receiver sensitivity numbers in AWGN for the highest data rate in each operating frequency band shall be the numbers listed in Table 18. The minimum input levels are measured at the antenna connector, where a noise figure of 10 dB (referenced at the antenna) and an implementation loss of 6 dB have been assumed.

Table 18 — Receiver Sensitivity Numbers

Frequency Band (MHz)	Information Data Rate (kbps)	Minimum Sensitivity (dBm)
2360 – 2483.5	1022.6	-86
402 – 405	425.6	-87
902 – 928	766.9	-84
950 – 956	607.1	-85
863 – 870	303.6	-88

5.2   Adjacent Channel Rejection

The adjacent channel rejection shall be measured by setting the desired signal's strength 3 dB above the rate-dependent sensitivity specified in Table 18 and raising the power of the interfering signal until a 10% PER is reached for a PSDU length of 255 bytes. The power difference between the interfering and the desired channel is the corresponding adjacent channel rejection. The interfering signal in the adjacent channel shall be a conformant PHY signal at the same information data rate, unsynchronized with the signal in the channel under test. For a compliant PHY, the corresponding adjacent channel rejection shall be no less than the numbers specified in Table 19.

Table 19 — Receiver Adjacent Channel Rejection Numbers

Frequency Band (MHz)	Information Data Rate (kbps)	Adjacent Channel Rejection (dB)
2360 – 2483.5	1022.6	7
402 – 405	425.6	2
902 – 928	766.9	2
950 – 956	607.1	2
863 – 870	303.6	2

5.3   Receiver Energy Detection

The receiver energy detection (ED) measurement is an estimate of the received signal power within the bandwidth of the channel. It is intended for use by a network/MAC layer as part of a channel selection algorithm. No attempt is made to identify or decode signals on the channel.

5.3.1   ED Threshold

The minimum ED value (zero) shall indicate received power less than either

- 10 dB above the specified receiver sensitivity (see Section 5.1) OR

- that which is prescribed by local regulatory requirements,

which ever is lower.

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.

5.3.2   ED Measurement Time

The ED measurement time, to average over, shall be either

- 8 preamble symbol periods OR

- that which is prescribed by local regulatory requirements,

which ever is longer in duration.

5.4   Receiver Clear Channel Assessment

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

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 compliant with this standard with the same modulation and characteristics of the PHY that is currently in use by the device. This signal may be above or below the ED threshold. The CCA detection time shall be equal to pCCATime.

CCA Mode 3: Carrier sense with energy above threshold. CCA shall report a busy medium using a logical combination of

a.   Detection of a signal with the modulation and characteristics of this standard and

b.   Energy above the ED threshold, where the logical operator may be AND or OR.

The CCA parameters are subject to the following criteria:

a) The ED threshold shall correspond to a received signal power as prescribed in section 5.3.1.

b) The CCA detection time shall be equal to pCCATime (see Section 3.2).

Annex: Comparison Criteria

1. Regulatory – Compliance to TG6 regulatory document (08-0034)

   The proposed PHY complies with all local regulations, but not limited to:
   - FCC 47 CFR Part 15
   - FCC 47 CFR Part 95
   - ETSI EN 300 440-1 v1.5.1
   - ETSI EN 301 839-1 v1.2.1
   - ETSI EN 300 220-1 v2.1.1
   - ARIB STD-T96 Ver 1.0

2. Raw PHY data rate (node to node)

   The proposed PHY support scalable information data rates from 100 kbps – 1000 kbps.

3. Transmission distance between two nodes

   The proposed PHY supports a minimum distance of 3 meters for all data rates. See link budget section for more details.

4. Packet error rate (PER)

   The PER performance for an AWGN channel is shown in Figure 11 through Figure 13 as a function of SNR and the constellation size and coding rate, which corresponds to data rate. All simulations were performed over 20000 packets with a PSDU = 256 bytes. The assumptions for the simulations included ideal packet detection, ideal header decoding, ideal symbol and zero carrier-frequency offset.
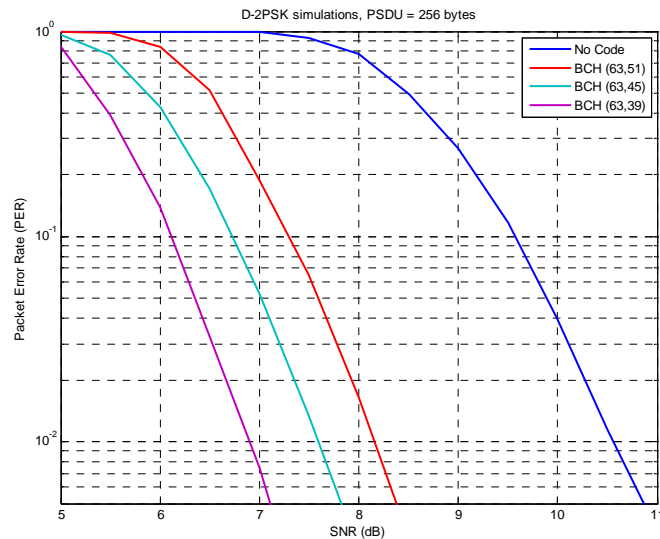
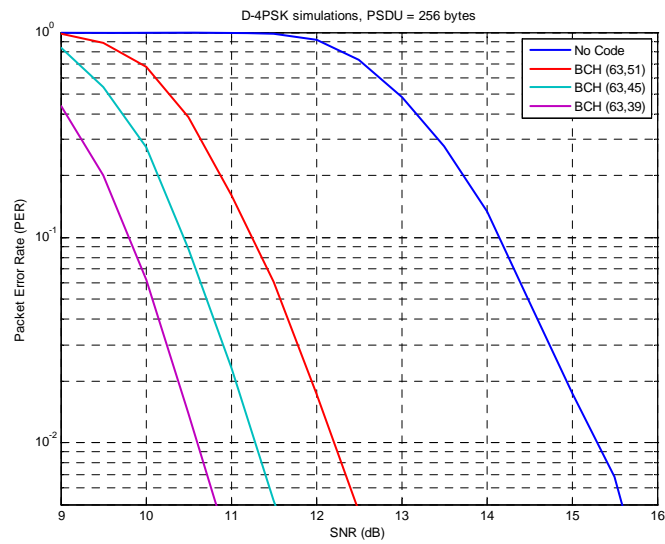**Figure 11 — PER curves for π/2-DBPSK and various code rates**

Figure: D-4PSK simulations, PSDU = 256 bytes. Packet Error Rate (PER) vs SNR (dB). Curves: No Code, BCH (63,51), BCH (63,45), BCH (63,39).

Figure 12 — PER curves for π/4-DQPSK and various code rates

Figure: D-8PSK simulations, PSDU = 256 bytes. Packet Error Rate (PER) vs SNR (dB). Curves: No Code, BCH (63,51), BCH (63,45), BCH (63,39).

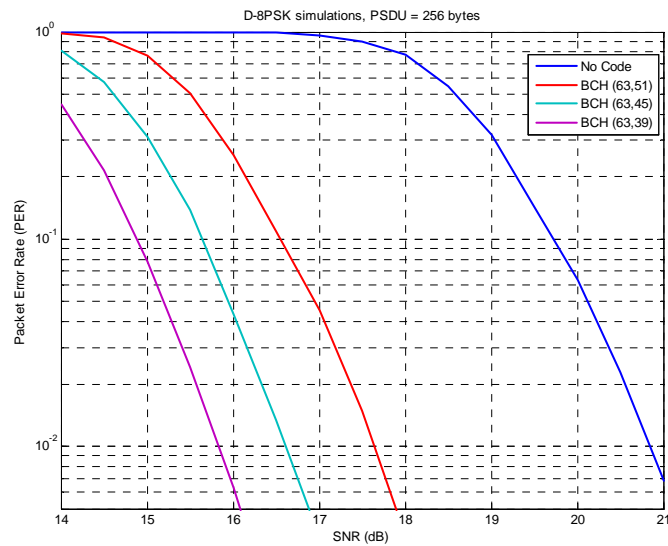Figure 13 — PER curves for π/8-D8PSK and various code rates

5. Link Budget and Reliability

Assumptions: AWGN, 0 dBi TX and RX antennas, free-space path loss. Link budget table for 2360 – 2483.5 MHz:

Parameter	Value	Value	Value	Value
Data Rate (Rb) [kbps]	127.8	255.6	511.3	1022.6
Average TX Power (PT) [dBm]	-10.52	-10.52	-10.52	-11.20
TX Antenna Gain (GT) [dBi]	0	0	0	0
Center Frequency (fc) [MHz]	2480	2480	2480	2480
Distance Outside Body (d1) [m]	3	3	3	3
Path Loss @ d1 meters (L1 = 20*log10(4*pi*d*fc/c) [dB]	49.87	49.87	49.87	49.87
Rx Antenna Gain (GR) [dBi]	0	0	0	0
RX Power: PR = PT + GT + GR - L1 [dBm]	-60.39	-60.39	-60.39	-61.07
Average Noise Power (N = -174 + 10*log10(BW)) [dBm]	-114.40	-114.40	-114.40	-114.13
RX Noise Figure (NF) [dB]	10	10	10	10
Total Noise Power(PN = N + NF) [dBm]	-104.40	-104.40	-104.40	-104.13
Minimum SNR (S) [dB]	2.80	4.80	7.30	11.20
Implementation Loss (I) [dB]	6	6	6	6
Link Margin (M = PR - PN - S - I) [dB]	35.20	33.20	30.70	25.86
Proposed Minimum RX Sensitivity Level (PS = PR-M) [dBm]	-95.60	-93.60	-91.10	-86.93

Assumptions: AWGN, 0 dBi TX and RX antennas, free-space path loss, path loss inside the body value stated in A. J. Johansson, "Wireless communication with medical implants: Antenna and propagation," ISSN 1402-8662, 2004. Link budget table for 402 – 405 MHz:

Parameter	Value	Value	Value	Value
Data Rate (Rb) [kbps]	126.1	252.1	352.9	428.6
Average TX Power (PT) [dBm]	-16.00	-16.00	-16.00	-16.00
TX Antenna Gain (GT) [dBi]	0	0	0	0
Center Frequency (fc) [MHz]	406	406	406	406
Distance Inside Body (d0) [mm]	20	20	20	20
Path Loss @ d0 meters (L0) [dB]	34	34	34	34
Distance Outside Body (d1) [m]	3	3	3	3
Path Loss @ d1 meters (L1 = 20*log10(4*pi*d*fc/c) [dB]	34.15	34.15	34.15	34.15
Rx Antenna Gain (GR) [dBi]	0	0	0	0
RX Power: PR = PT + GT + GR - L0 - L1 [dBm]	-84.15	-84.15	-84.15	-84.15
Average Noise Power (N = -174 + 10*log10(BW)) [dBm]	-119.96	-119.60	-119.60	-119.60
RX Noise Figure (NF) [dB]	10	10	10	10
Total Noise Power(PN = N + NF) [dBm]	-109.96	-109.60	-109.60	-109.60
Minimum SNR (S) [dB]	6.70	10.40	14.10	16.50
Implementation Loss (I) [dB]	6	6	6	6
Link Margin (M = PR - PN - S - I) [dB]	13.10	9.04	5.34	2.94
Proposed Minimum RX Sensitivity Level (PS = PR-M) [dBm]	-97.26	-93.20	-89.50	-87.10

Assumptions: AWGN, 0 dBi TX and RX antennas, free-space path loss. Link budget table for 902 – 928 MHz:

Parameter	Value	Value	Value	Value
Data Rate (Rb) [kbps]	127.8	255.6	511.3	766.9
Average TX Power (PT) [dBm]	-10.52	-10.52	-11.31	-11.81
TX Antenna Gain (GT) [dBi]	0	0	0	0
Center Frequency (fc) [MHz]	928	928	928	928
Distance Outside Body (d1) [m]	3	3	3	3
Path Loss @ d1 meters (L1 = 20*log10(4*pi*d*fc/c) [dB]	41.34	41.34	41.34	41.34
Rx Antenna Gain (GR) [dBi]	0	0	0	0
RX Power: PR = PT + GT + GR - L1 [dBm]	-51.86	-51.86	-52.65	-53.15
Average Noise Power (N = -174 + 10*log10(BW)) [dBm]	-117.41	-117.41	-117.16	-117.07
RX Noise Figure (NF) [dB]	10	10	10	10
Total Noise Power(PN = N + NF) [dBm]	-107.41	-107.41	-107.16	-107.07
Minimum SNR (S) [dB]	4.80	7.30	11.20	16.50
Implementation Loss (I) [dB]	6	6	6	6
Link Margin (M = PR - PN - S - I) [dB]	44.75	42.25	37.31	31.42
Proposed Minimum RX Sensitivity Level (PS = PR-M) [dBm]	-96.61	-94.11	-89.96	-84.57

Assumptions: AWGN, 0 dBi TX and RX antennas, free-space path loss. Link budget table for 950 – 956 MHz:

Parameter	Value	Value	Value	Value
Data Rate (Rb) [kbps]	154.8	250.0	500.0	607.1
Average TX Power (PT) [dBm]	-10.52	-11.18	-11.18	-11.56
TX Antenna Gain (GT) [dBi]	0	0	0	0
Center Frequency (fc) [MHz]	956	956	956	956
Distance Outside Body (d1) [m]	3	3	3	3
Path Loss @ d1 meters (L1 = 20*log10(4*pi*d*fc/c) [dB]	41.59	41.59	41.59	41.59
Rx Antenna Gain (GR) [dBi]	0	0	0	0
RX Power: PR = PT + GT + GR - L1 [dBm]	-52.11	-52.77	-52.77	-53.15
Average Noise Power (N = -174 + 10*log10(BW)) [dBm]	-118.42	-118.17	-118.17	-118.02
RX Noise Figure (NF) [dB]	10	10	10	10
Total Noise Power(PN = N + NF) [dBm]	-108.42	-108.17	-108.17	-108.02
Minimum SNR (S) [dB]	6.10	9.60	14.10	16.50
Implementation Loss (I) [dB]	6	6	6	6
Link Margin (M = PR - PN - S - I) [dB]	44.21	39.80	35.30	32.36
Proposed Minimum RX Sensitivity Level (PS = PR-M) [dBm]	-96.32	-92.57	-88.07	-85.52

Assumptions: AWGN, 0 dBi TX and RX antennas, free-space path loss. Link budget table for 863 – 870 MHz:

Parameter	Value	Value	Value	Value
Data Rate (Rb) [kbps]	101.2	178.6	250.0	303.6
Average TX Power (PT) [dBm]	-10.52	-11.18	-11.18	-11.56
TX Antenna Gain (GT) [dBi]	0	0	0	0
Center Frequency (fc) [MHz]	870	870	870	870
Distance Outside Body (d1) [m]	3	3	3	3
Path Loss @ d1 meters (L1 = 20*log10(4*pi*d*fc/c) [dB]	40.77	40.77	40.77	40.77
Rx Antenna Gain (GR) [dBi]	0	0	0	0
RX Power: PR = PT + GT + GR - L1 [dBm]	-51.29	-51.95	-51.95	-52.33
Average Noise Power (N = -174 + 10*log10(BW)) [dBm]	-121.45	-121.18	-121.18	-121.01
RX Noise Figure (NF) [dB]	10	10	10	10
Total Noise Power(PN = N + NF) [dBm]	-111.45	-111.18	-111.18	-111.01
Minimum SNR (S) [dB]	7.30	10.40	14.10	16.50
Implementation Loss (I) [dB]	6	6	6	6
Link Margin (M = PR - PN - S - I) [dB]	46.86	42.83	39.13	36.17
Proposed Minimum RX Sensitivity Level (PS = PR-M) [dBm]	-98.15	-94.78	-91.08	-88.51

The channel fading statistics were calculated using the CM4 (on-body to external device) channel models. The channel gains were averaged over all orientations (0º, 90º, 180º, 270º). The transmitter was located on the chest and the patient was standing. The assumed velocity was 1 km/hr. In the following table, the free-space path loss was removed from the gain, since it is already incorporated into the AWGN link budget tables.

The results for the 90%-tile, 95%-tile and 99%-tile fade depth at 3 meters are given in Table 20.

Table 20 — Channel Fading Statistics

Frequency Band (MHz)	90% Fade Depth at 3 meters	90% Fade Depth at 3 meters	90% Fade Depth at 3 meters
2360 – 2483.5	17.1 dB	17.5 dB	19.0 dB
902 – 928	18.8 dB	19.0 dB	19.5 dB
950 – 956	18.6 dB	18.7 dB	19.2 dB
863 – 870	19.4 dB	19.5 dB	20.0 dB

Table 21, which is the link budget in realistic channel environments, shows that the proposed PHY has sufficient link margin at 3 meters, even with 99% fade depth, and therefore, can provide an operating range of at least 3 meters for all data rates.

Table 21 — Link Budget in Realistic Channel Environments

Parameter	Value	Value	Value	Value	Value	Value	Value	Value
Center Frequency (fc) [MHz]	2480	2480	928	928	956	956	870	870
Data Rate (Rb) [kbps]	127.8	1022.6	127.8	766.9	154.8	607.1	101.2	303.6
AWGN Link Margin [dB]	35.2	25.9	44.8	31.4	44.2	32.4	46.9	36.2
99% Fade Depth at 3 meters	19.0	19.0	19.5	19.5	19.2	19.2	20.0	20.0
Link Margin [dB]	16.2	6.9	25.3	11.9	25.0	13.2	26.9	16.2

6. Power Emissions Level

The proposed PHY meets at local regulations, including regulations on SAR.

7. Interference and coexistence

This document specifies the receiver adjacent channel rejection numbers in Table 19. These number specify the power levels, with respect to the power of the desired device, that can be tolerated on an adjacent channel and still satisfy a PER of 10% with a PSDU of 256 bytes, given a 3 dB margin above sensitivity.

Table 22 lists the required distance and frequency separation from the interfering device that is required in order to maintain a PER of 10% with a PSDU of 256 bytes, given a 6 dB margin above sensitivity.

Table 22 — Distance and Frequency Separation Required from Interfering Devices

Interferer	Value
IEEE 802.11g @ 2.4 GHz, Ptx = +15 dBm	dint $\leq$ 8.0 m ($\downarrow$), fsep $\geq$ 22 MHz ($\uparrow$)
Bluetooth @ 2.4 GHz, Ptx = 0 dbm	dint $\leq$ 0.3 m ($\downarrow$), fsep $\geq$ 2 MHz ($\uparrow$)

8. Multiple Co-located Network Support

Each of the proposed frequency bands supports a minimum of 10 channels:

– 2400 – 2483.5 MHz: 79 channels

– 2360 – 2400 MHz: 38 channels

– 402 – 405 MHz: 10 channels

– 902 – 928 MHz: 48 channels

– 950 – 956 MHz: 12 channels

– 863 – 870 MHz: 15 channels

Multiple co-located networks can be supported via frequency-division multiple access (FDMA).

9. Scalability

Four data rates are provided within each frequency band.

10. Power Efficiency

Frequency Band (MHz)	Data Rate (kbps)	TX	RX	Standby	Deep Sleep
2360 – 2483.5	1022.6	2.9 mW	3.1 mW	50 μW	250 nW
902 – 928 950 – 956 863 – 870	733.1 607.1 303.6	2.2 mW	2.5 mW	50 μW	250 nW
402 – 405	428.6	1.9 mW	2.1 mW	50 μW	125 nW