**IEEE P802.15**

**Wireless Personal Area Networks**

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**History:**

**R0: Initial submission.**

**R1: Rewritten the text to get compatible with the styles of existing PHYs in the draft.**

**R2: Comments from IEEE Sep. meeting applied.**

5.7.3 LB-PHY introduction

The LB-PHY, specified in Clause 11, is intended for low data rate applications with data rates in the tens of Mb/s using bit-interleaved coded modulation based on OFDM. It supports efficient utilization of the low-bandwidth resources (up to 32 MHz of single-sided bandwidth) of high-power LEDs. The unique approach of the LB-PHY is to combine a low bandwidth with low-complexity, high energy efficiency and enhanced reliability. DC-biased OFDM as defined in 11.3.4.1 is supported as the default waveform, while an enhanced unipolar OFDM (eU-OFDM), as defined in 11.3.4.2 is also supported as an optional alternative waveform for the payload only. The eU-OFDM mode can be switched to via the indication in the advanced modulation header. The LB-PHY supports MIMO transmissions via multiple OFEs.

7.2.23 LB-PHY MCS List element

The LB-PHY MCS List element, shown in Figure 57, holds a subset of supported MCS for the LB-PHY.

|  |
| --- |
| **1 Octet** |
| Clock Rates |

**Figure 57 LB-PHY MCS List element**

**Clock Rates**: A bitmap indicating the set of supported clock rates. Reserved bits shall be set to zero. A one in the bitmap indicates that the given clock rate is supported. A zero indicates that the clock rate is not supported. Figure 58 shows the bitmap structure.

**Octet 1, LSB left**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Bit in the bitmap** | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **Clock Rates** | 1 MHz | 2 MHz | 4 MHz | 8 MHz | 16 MHz | 20 MHz | 25 MHz | 32 MHz |

**Figure 58 Clock rate bitmap**

1. **LB-PHY specifications**
2. **1 General information**

**11.1.1 Overview**

The LB-PHY enables data rates in the tens of Mb/s for low data rate applications using OFDM modulation. The main approach is to achieve efficient utilization of the low-bandwidth resources (up to 32 MHz of single-sided bandwidth) by using a low clock rate and a highly adaptive modular implementation. This approach offers a low-complexity on the PHY to enable high spectrum efficiency and enhanced transmission reliability for low data rate applications.

The default waveform is a DC-biased OFDM, while the eU-OFDM waveform can be used as an optional alternative which can be switched to via the indicator in the advanced modulation header. The LB-PHY includes means to adapt the data rate of the link to varying channel conditions by varying the clock rate, the code rate and the modulation. The LB-PHY supports MIMO transmissions via multiple OFEs.

The LB-PHY operating modes are summarized in Table 46.

**Table 46 Summary of the LB-PHY**

|  |  |
| --- | --- |
| **Modulation** | DC-biased OFDM, eU-OFDM |
|  |  |
|  |  |
|  |  |
| **FEC** | Convolutional coding |
| **Code rates** | 1/2, 2/3, 3/4 |
|  |  |
|  |  |
|  |  |
| **Modulation** | **FEC** | **Clock rate** | **Data rate** |
| **Min.** | **Max.** |
| BPSK | Inner convolutional code (1/2) | 1-32 MHz | 0.3 Mb/s | 9.6 Mb/s |
| BPSK | Inner convolutional code (3/4) | 0.45 Mb/s | 14.4 Mb/s |
| QPSK | Inner convolutional code (1/2) | 0.6 Mb/s | 19.2 Mb/s |
| QPSK | Inner convolutional code (3/4) | 0.9 Mb/s | 28.8 Mb/s |
| 16-QAM | Inner convolutional code (1/2) | 1.2 Mb/s | 38.4 Mb/s |
| 16-QAM | Inner convolutional code (3/4) | 1.8 Mb/s | 57.6 Mb/s |
| 64-QAM | Inner convolutional code (2/3) | 2.4 Mb/s | 76.8 Mb/s |
| 64-QAM | Inner convolutional code (3/4) | 2.7 Mb/s | 86.4 Mb/s |

Clock rates have the range between 1 and 32 MHz as listed in Table 48, which can be selected as in sub-clause 7.2.23. The diagram of the DC-biased OFDM system is illustrated in Figure 75.



**Figure 75 Diagram of the DC-biased OFDM system**

**11.1.2 Base MCS**

The base MCS for the LB-PHY shall be binary phase shift keying (BPSK) with code rate 1/2, i.e., MCS ID 000 as defined in Table 49.

**11.1.3 PHY constants**

Table 47 lists the PHY constants for the LB-PHY.

**Table 47 LB-PHY constants**

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Description** | **Value** | **Unit** |
| *aPhyMaxPsduSize* | The maximum supported PSDU size.  | 2036 | octets |
| *aPhyMifsDuration* | The duration of the MIFS for transmissions using the HB-PHY. | 3 | µs |
| *aPhyMinPsduSize* | The minimum supported PSDU size.  | 20 | octets |
| *aPhyTurnaroundTime* | The maximum time required to switch the PHY from TX mode to RX mode or from RX mode to TX mode. This is not required in the full duplex mode.  | 10 | µs |
| *aPhyClockAccuracy* | The minimum accuracy of the PHY reference clock. | ±20 | ppm |

**11.1.4 PHY PIB attributes**

Table 48 lists the PHY PIB attributes for the LB-PHY.

**Table 48 PHY PIB attributes for the LB-PHY**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Name** | **Description** | **get/set**  | **Range**  | **Unit** |
| *phyClockRate* | The clock rate | get / set | 1, 2, 4, 8, 16, 20, 25, 32 | MHz |

* 1. **PPDU format**

**11.2.1 Overview**

The LB-PHY transmits PPDUs that consist of multiple fields. The PPDU format is shown in Figure 76. A *preamble* serves detection and gain adjustment. The *Channel Estimation field* allows subsequent measurement of the effective channel. The *PHY Header field* includes information that is necessary to demodulate, decode, and interpret the rest of the PPDU. *Explicit MIMO pilots* aid in estimating the MIMO channel from multiple transmitters. Finally, the *Payload* field carries the coded and modulated PSDU.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Preamble** | **Channel Estimation** | **PHY Header** | **Explicit MIMO pilots** | **Payload** |

**Figure 76 PPDU format for LB-PHY**

* + 1. **Bit order**

Header fields that contain numbers shall be transmitted starting with the LSB first to the MSB last.

The PSDU consists of an ordered sequence of octets. Within each octet of the PSDU, the LSB of each octet shall be transmitted first.

**11.2.3 Preamble**

The LB-PHY preamble consists of pseudo noise training sequence, which lasts for the duration equivalent of two OFDM symbols. The sequence in preamble field is a time domain sequence and does not have any channel coding or line coding.

The following demonstrates the generation of pseudo noise training sequences.

Step 1: Select two 20-bit pseudo noise sequences:

Other pseudo noise sequences can be used as an option.

*pn\_seq*0 = 20'*b*01001011000001110111

*pn\_seq*1 = 20'*b*01101100111101010000

Step 2: Up-sample the above sequences by 8

Step 3: Pulse shape with the following pulse {-479, 416, -10, -409, 67, -409, -10, 416}

Step 4: Flip the sequence at the end of Step 3, e.g., (*x1*, ..., *xn*, *xn*, …, *x1*), in order to get two sequences for each original pseudo noise sequences (i.e., *pn\_seq0* and *pn\_seq1*).

**11.2.4 Channel estimation**

The Channel Estimation field consists of two repetitions of a “Hermitian symmetric long training sequence” preceded by a cyclic prefix.

A sequence of two identical OFDM training symbols is used to estimate the channel impulse response, as well as for additional fine-timing synchronization. The channel estimation sequence shall contain the following values modulated on the subcarriers of two identical Inverse Fast Fourier Transforms (IFFTs). Index 0 corresponds to the DC subcarrier modulation value.

**11.2.5 PHY header**

The PHY header is encoded in 1/2 FEC rate BPSK modulation using DC-biased OFDM.

**11.2.5.1 Basic LB-PHY header**

If LB-PHY is used, the following information shall be provided in all PHY frames. The basic header contains 48 bits. The information bits contained in the basic PHY header are as specified in Figure 78.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Bit 0-2** | **Bit 3-13** | **Bit 14** | **Bit 15-17** | **Bit 18-40** | **Bit 41** | **Bit 42-47** |
| MCS ID | PSDU Length | Advanced Modulation Header | Explicit MIMO Pilot Slots | Reserved | Parity | Tail |

**Figure 78 Fields in the basic LB-PHY header**

The individual fields are defined as follows:

**MCS ID:** This field indicates the QAM constellation size and the FEC rate used for the subsequent payload. MCS ID values are specified in Table 49.

**Table 49 Valid MCS ID values**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **MCSIDb0-b2** | **Modulation** | **FEC rate** | **Data rate at 1 MHz clock rate** | **Data rate at 16 MHz clock rate** | **Data rate at 20 MHz clock rate** | **Data rate at 32 MHz clock rate** |
| 000 | BPSK | Inner convolutionalcode (1/2) | 0.3 Mb/s | 4.8 Mb/s | 6 Mb/s | 9.6 Mb/s |
| 001 | Inner convolutionalcode (3/4) | 0.45 Mb/s | 7.2 Mb/s | 9 Mb/s | 14.4 Mb/s |
| 010 | QPSK | Inner convolutionalcode (1/2) | 0.6 Mb/s | 9.6 Mb/s | 12 Mb/s | 19.2 Mb/s |
| 011 | Inner convolutionalcode (3/4) | 0.9 Mb/s | 14.4 Mb/s | 18 Mb/s | 28.8 Mb/s |
| 100 | 16-QAM | Inner convolutionalcode (1/2) | 1.2 Mb/s | 19.2 Mb/s | 24 Mb/s | 38.4 Mb/s |
| 101 | Inner convolutionalcode (3/4) | 1.8 Mb/s | 28.8 Mb/s | 36 Mb/s | 57.6 Mb/s |
| 110 | 64-QAM | Inner convolutionalcode (2/3) | 2.4 Mb/s | 38.4 Mb/s | 48 Mb/s | 76.8 Mb/s |
| 111 | Inner convolutionalcode (3/4) | 2.7 Mb/s | 43.2 Mb/s | 54 Mb/s | 86.4 Mb/s |

**PSDU Length:** The PSDU Length scales from zero up to *aPhyMaxPsduSize* and indicates the length of the PSDU in octets.

**Advanced Modulation Header:** This field indicates whether an Advanced Modulation Header shall exist following the basic PHY header. If Advanced Modulation Header equals one, Advanced Modulation Header shall be added after the basic PHY header. If Advanced Modulation Header equals zero, Advanced Modulation Header does not appear after the basic PHY header.

**Explicit MIMO Pilot Slots**: This field specifies the number of slots for explicit MIMO pilots in the PPDU.

**Parity**: This field does an even parity check for the information in bits 0 - 16.

**Tail**: This fieldconsists of six bits, which are set to zero to complete the basic PHY header.

**11.2.5.2 The Advanced Modulation Header**

The Advanced Modulation Header is encoded in separate OFDM symbols from the basic PHY header. The advanced modulation header is also encoded using 1/2 FEC rate BPSK. The advanced modulation header contains the information necessary for demodulating the subsequent waveform.

The advanced modulation header consists of the fields given in Figure 79.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Bit 0** | **Bit 1** | **Bit 2** | **Bit 3** | **Bit 4-9** | **Bit 10** | **Bit 11-12** | **Bit 13** | **Bit 14-16** | **Bit 17** | **Bit 18-23** |
| reserved | CQI | eU-OFDM | STR | reserved | RelayingEnabled | RelayingMode | MIMOPilotSymbol | reserved | Parity | Tail |

**Figure 79 Fields in the advanced modulation header**

The individual fields are defined as follows:

**CQI**: This field indicates whether the CQIs shall be calculated in the LB-PHY for the current transmission frame.

0b1 indicates that the CQIs shall be estimated.

0b0 indicates that no CQIs need to be estimated.

**eU-OFDM**: This field indicates whether the payload field is encoded with eU-OFDM.

0b1 indicates that the payload is encoded with eU-OFDM.

0b0 indicates that the payload is not encoded with eU-OFDM.

**STR**: This field indicates the number of eU-OFDM streams superimposed in the signal encoding procedure.

0b0 indicates: the number of eU-OFDM streams superimposed in the signal encoding procedure is one.

0b1 indicates: the number of eU-OFDM streams superimposed in the signal encoding procedure is four.

**Relaying Enabled**: This field indicates whether a relaying mode is enabled for the current PHY frame.

**Relaying mode**: This field specifies the type of relaying mode that shall be performed.

0b00 indicates that the relaying and duplexing mode is FD-AF.

0b01 indicates that the relaying and duplexing mode is FD-DF.

0b10 indicates that the relaying and duplexing mode is HD-AF.

0b11 indicates that the relaying and duplexing mode is HD-DF.

**MIMO Pilot Symbols**: This field Format bit indicates the format of the pilot symbols used for CQI estimation.

0b0 indicates that the MIMO pilot symbols format I is used.

0b1 indicates that the MIMO pilot symbols format II is used.

**Parity**: This field does an even parity check for the information in bits 0 - 16.

**Tail**: This field consists of six bits, which are set to zero to complete the advanced modulation header.

**11.2.6 Explicit MIMO pilots**

**11.2.6.1 Overview**

A PPDU may include up to eight OFDM symbols in order to support MIMO channel estimation for multiple OFEs. The number of OFDM symbols NPS used for explicit MIMO pilots in the PPDU shall be indicated by the Explicit MIMO Pilot Symbol Number field in the PHY header.

The Explicit MIMO Pilots field of the PPDU contains NPS = 0, 1, 2, 3, 4, 5, 6, 7 OFDM symbols for estimation of the MIMO channel between multiple transmitting and receiving OFEs. Explicit MIMO pilots follow the PHY header data field as depicted in Figure 76. Explicit MIMO pilots are defined in the frequency and time domains in an orthogonal manner so that they can be transmitted from multiple OFEs simultaneously. The two MIMO pilot symbols formats are defined as follows.

**11.2.6.2 MIMO Pilot Symbols Format I**

For each OFE, only one OFDM symbol interval is set to the desired channel estimation sequence. All other intervals are set to zero. The format is illustrated in Figure 80.



**Figure 80 MIMO pilot symbols format I**

**11.2.6.3 MIMO Pilot Symbols Format II**

For each OFE, every frame interval is set to the desired channel estimation sequence. In addition, the channel estimation sequences for each transmitter are modified by adjusting the polarity of the individual channel estimation sequence sequences according to a pre-determined set of Walsh sequences, where a value of one in the Walsh sequence corresponds to an unmodified channel estimation sequence while a value of minus one corresponds to a channel estimation sequence with reverse polarity. The format is presented in Figure 81. The channel estimation sequences in white are left unmodified, while the channel estimation sequences in gray are multiplied by -1.



**Figure 81 MIMO pilot symbols format II**

The Walsh sequences for a MIMO configuration with two transmitters (*N*MIMO = 2) correspond to the rows of the matrix *W*2 MIMO:

The Walsh sequences for a MIMO configuration with four transmitters (*N*MIMO= 4) correspond to the rows of the matrix *W*4 MIMO:

The Walsh sequences for a MIMO configuration with eight transmitters (*N*MIMO = 8) correspond to the rows of the matrix W8 MIMO:

The Walsh sequences for a MIMO configuration with transmitters () correspond to the rows of the matrix :

* + 1. **Payload**

The payload contains the PSDU as received from the higher layer. Payload is transmitted at one of the supported data rates. The modulation and coding parameters for the payload are indicated in the PHY header.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  |  |  |
|  |  |  |  |  |

* + - 1.

**11.3 Modulation and coding**

**11.3.1 Interleaving**

OFDM is invariably used in conjunction with [channel coding](https://en.wikipedia.org/wiki/Channel_coding) ([forward error correction](https://en.wikipedia.org/wiki/Forward_error_correction)), and usually applies frequency and/or time [interleaving](https://en.wikipedia.org/wiki/Forward_error_correction#Interleaving).

All encoded data bits shall be interleaved by a block interleaver with a block size corresponding to the number of bits in two OFDM symbols, . The interleaver is defined by a two-step permutation. The first permutation ensures that adjacent coded bits are mapped onto nonadjacent subcarriers. The second ensures that adjacent coded bits are mapped alternately onto less and more significant bits of the constellation and, thereby, long runs of low reliability bits, i.e. LSBs, are avoided. The index of the coded bit before the first permutation shall be denoted by ; shall be the index after the first and before the second permutation; and shall be the index after the second permutation, prior to modulation mapping.

The first permutation is defined by,

.

The function floor (.) denotes the largest integer not exceeding the parameter.

The second permutation is defined by,

The value of is determined by the number of coded bits per subcarrier, , according to,

The de-interleaver, which performs the inverse relation, is also defined by two permutations.

Here the index of the original received bit before the first permutation shall be denoted by ; shall be the index after the first and before the second permutation; and shall be the index after the second permutation, just prior to delivering the coded bits to the convolutional (Viterbi) decoder. The first permutation is defined by,

.

The second permutation is defined by,

.

**11.3.2 Forward error correction (FEC)**

The PPDU shall be encoded with a convolutional encoder of coding rate R = 1/2, 2/3, or 3/4, corresponding to the desired data rate. The convolutional encoder shall use the industry-standard generator polynomials, g0 = 1338 and g1 = 1718, of rate R = 1/2, as shown in Figure 85. The bit denoted as "A" shall be output from the encoder before the bit denoted as "B". The summation operation presented in Figure 85 is a modulo-2 summation, i.e., an XOR operation. A subscript eight denotes octal values.

Higher rates shall be derived from this encoding mechanism by employing "puncturing." Puncturing is a procedure for omitting some of the encoded bits in the transmitter (thus reducing the number of transmitted bits and increasing the coding rate) and inserting a dummy zero metric into the convolutional decoder on the receive side in place of the omitted bits. The puncturing patterns are illustrated in Figure 86. Decoding by the Viterbi algorithm is recommended.



**Figure 85 Convolution encoder (1338,1718)**



**Figure 86 Puncturing (bit stealing) algorithm**

**11.3.3 payload**

payload. The PHY payload scramblerFigure 87

**Figure 87 payload**

. In the initial state, the whole sequence is in 1’s.

**11.3.4 OFDM modulator**

**11.3.4.1 DC-biased OFDM modulator**

The approach for modulating the LED active range with an OFDM signal is to set a positive operating point, around which the bipolar OFDM signal can be realized as illustrated in Figure 88.



**Figure 88 DC-biased OFDM**

The IDFT size is fixed in the LB-PHY mode to enable lower implementation complexity. The modulation of the different frequency-domain subcarriers is achieved through an IDFT operation, described as follows:

where is the symbol mapped to subcarrier index . Conventionally, the IDFT is implemented with an IFFT algorithm.

The DFT/IDFT size in the current PHY mode is fixed to 64.

Subcarriers with negative indices -28 to -3 are loaded with 24 data symbols and two pilots. The pilots are located at index -21 and -7. Subcarriers with positive indices 3 to 28 are loaded with the conjugate complex of the data and pilot symbols at the negative indices. The pilot symbols have all value one.

Subcarriers with indices -2, -1, -1, 2 are set to zero in order to avoid possible low-frequency distortion in the system due to baseline wandering and background light interference.

Subcarriers -31, -30, -29, 29, 30, 31 are set to zero because those are near the band edge of the low pass filters in the system and may get attenuated excessively. Subcarriers with index 0, i.e. DC, and -32 are also set to zero. The mapping is illustrated in Figure 89.



**IDFT realization by means of an IFFT algorithm**

**11.3.4.2 Enhanced unipolar OFDM (eU-OFDM)**

The eU-OFDM is an optional alternative modulation approach. It turns the bipolar OFDM signal into a strictly unipolar information signal without the addition of an energy intensive DC component.

The transmitter sends the new transmission PHY mode to the receiver using the eU and STR bits in the advanced modulation PHY header. For conformance purposes, the preamble and the PHY headers are encoded in a DC-biased OFDM fashion. Following the four BPSK OFDM symbols containing the PHY header, as well as the MIMO pilot symbols when applicable, the payload field is encoded in an eU-OFDM fashion, as shown in Figure 90.



**Figure 90 Enhanced Unipolar OFDM (eU-OFDM)**

**11.3.4.3 Data stream mapping with one stream for eU-OFDM**

A single eU-OFDM stream is specified by STR = '0' in the advanced modulation header. Two consecutive copies of every OFDM symbol shall be generated. The polarity of the samples in the second copy is inverted. All negative samples in the resulting time-domain signal shall be set to zero. The resulting positive signal is used to modulate the transmitter as illustrated in Figure 91.



**Figure 91 Unipolar OFDM generation (1 stream)**

**11.3.4.4 Data stream mapping with two streams for eU-OFDM**

The two eU-OFDM streams cases group every three OFDM symbols into an eU-OFDM block. The first two symbols are assigned to data stream 1 (St1) and the third symbol is assigned to data stream 2 (St2). The two symbols in St1 are modulated using the algorithm described for single eU-OFDM stream. The symbol in St2 is modulated to four consecutive copies, where the first two copies are kept unchanged, while the polarity of the samples in the next two copies is inverted. The resulting positive signal is used to modulate the transmitter as illustrated in Figure 92.



**Figure 92 Unipolar OFDM generation (2 streams)**

**11.3.4.5 Data stream mapping with three streams for eU-OFDM**

The three eU-OFDM streams group every seven OFDM symbols into a eU-OFDM block. The first four symbols are assigned to data stream 1 (St1);the next two symbols are assigned to data stream 2 (St2); and the last symbol is assigned to data stream 3 (St3). The four symbols in St1 and the two streams in St2 are modulated using the algorithm described for 2 eU-OFDMstream case. The symbol in St3 is modulated to eight consecutive copies of that symbol, where the first four copies are left unchanged, while the polarity of the samples in the following four copies is reversed The resulting positive signal is used to modulate the transmitter as illustrated in Figure 93.



**Figure 93 Unipolar OFDM generation (3 streams)**

**11.3.4.6 Data stream mapping with four streams for eU-OFDM**

The four eU-OFDM streams case is indicated by STR = '1'. It groups every fifteen OFDM symbols into an eU-OFDM block. The first eight symbols are assigned to data stream 1 (St1); the next four symbols are assigned to data stream 2 (St2); the following two symbols are assigned to data stream 3 (St3); and the last symbol is assigned to data stream 4 (St4).

In the first stream, two consecutive copies of every OFDM symbol are transmitted, where the second copy is multiplied by -1 (the signs of all samples are inverted in the time domain) as described in the cases with one, two, or three streams.

In the second stream, four consecutive copies of every OFDM symbol are transmitted, where the first two copies of the symbol are trans mitted in their original format, while the signs of the time-domain samples of the third and the fourth copy are inverted, i.e., the samples are multiplied by -1 as described in the cases for two streams and for three streams.

In the third stream, eight consecutive copies of every OFDM symbol are transmitted, where the first four copies are conveyed in their original format, while the signs of the time-domain samples of the fifth, sixth, seventh and eighth copy are inverted, i.e., the samples are multiplied by -1 as described in the case for two streams.

In the fourth stream, sixteen consecutive copies of every OFDM symbol are transmitted, where the first eight copies are conveyed in their original format, while the signs of the time-domain samples of the ninth, tenth, eleventh and twelfth, thirteenth, fourteenth, fifteenth and sixteenth copy are inverted, i.e., the samples are multiplied by −1.

The resulting positive signal is used to modulate the transmitter.