**­IEEE P802.15**

**Wireless Personal Area Networks**

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| Abstract | [Proposal for LB-PHY in 802.15.13] | |
| Purpose | [Inform TG13 about most recent work.] | |
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1. **LB-PHY**

The Low Bandwidth OFDM PHY (LB-PHY) is intended for low date rate applications with data rates in the tens of Mb/s using OFDM modulation. OFDM specified by LB-PHY enables a highly adaptive modular implementation, which supports efficient utilization of the low-bandwidth resources (up to 32 MHz of single-sided bandwidth) as well as a low-complexity PHY designed to enable high energy efficiency and enhanced transmission reliability. A DC-biased Optical OFDM (DCO-OFDM) is the default waveform. Furthermore, the enhanced unipolar OFDM (eU-OFDM) waveform are supported. For modulation of the LED, multiple optical clock rates (OCR) are used. LB-PHY supports the application of adaptive bit and power loading techniques as well as multiple-input multiple-output (MIMO). In addition, PHY supports relaying functionality.

* 1. **General Information**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Low Bandwidth PHY Operating Modes** | | | | | |
| **Modulation** | | | DCO-OFDM, eU-OFDM | | |
| **FEC** | | | Convolutional Coding | | |
| **Code Rates** | | | 1/2, 2/3, 3/4 | | |
| **Subcarrier Spacing *FSC*** | | | 1 MHz | | |
| **Cyclic prefix (CP)** | | | 250 ns | | |
| **MIMO** | | | Up to 16 by 16 | | |
| **Modulation** | **FEC** | **Optical Clock Rate** | | **Data rate / Mbit/**s | | |
| **Min.** | **Max.** | |
| BPSK | Inner CC(1/2) | 1-32 MHz | | 0.3 | 9.6 | |
| BPSK | Inner CC(3/4) | 0.45 | 14.4 | |
| QPSK | Inner CC(1/2) | 0.6 | 19.2 | |
| QPSK | Inner CC(3/4) | 0.9 | 28.8 | |
| 16-QAM | Inner CC(1/2) | 1.2 | 38.4 | |
| 16-QAM | Inner CC(3/4) | 1.8 | 57.6 | |
| 64-QAM | Inner CC(2/3) | 2.4 | 76.8 | |
| 64-QAM | Inner CC(3/4) | 2.7 | 86.4 | |

**Table 1 Numerology for High Bandwidth PHY**

The range of the available OCRs is [1, 32] MHz. The OCR can be obtained by dividing the available frequency by 8. The data rates for are times of the data rates for OCR 1MHz in the above table for each MCS accordingly.

The diagram of the DCO-OFDM system is illustrated in Figure 1.

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Figure 1 Diagram of the DCO-OFDM system

* 1. **Carrier mapping**

The LB-PHY mode is required to support fixed carrier mapping. All subcarriers are designated for information transfer by a single communication node in an allocated time interval. No special carrier designation for multiple access techniques exists, and no special carriers are designated for control information. Depending on whether the current PHY implementation supports adaptive bit allocation for the carrier mapping procedure (an optional feature), the mapping can be described as follows.

If adaptive bit loading is not supported, the mapping applies as follows:

The QAM modulation symbols to which the binary information has been mapped are divided into groups of 24 symbols, where the original order at the output of the QAM modulation encoder is preserved. Each ordered group of 24 symbols is mapped to the ordered set of subcarrier indices [3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 22, 23, 24, 25, 26, 27, 28], where indices 7 and 21 are assigned to fixed pilot values of 1 and -1, respectively. Zeros are assigned to subcarrier indices [0,1,2,29,30,31,32,33,34,35,62,63]. The Hermitian symmetric sequence of the 26 symbols assigned to indices [3-28] is assigned to subcarrier indices [36-61].

If adaptive bit loading is supported, the mapping applies as follows:

The carrier mapping is determined by means of a bit allocation table negotiated and specified at the MAC layer protocol through an exchange of control and management frames.

* 1. **Interleaving**

OFDM is invariably used in conjunction with [channel coding](https://en.wikipedia.org/wiki/Channel_coding" \o "Channel coding) ([forward error correction](https://en.wikipedia.org/wiki/Forward_error_correction" \o "Forward error correction)), and almost always uses frequency and/or time [interleaving](https://en.wikipedia.org/wiki/Forward_error_correction" \l "Interleaving" \o "Forward error correction).

Frequency (subcarrier) interleaving increases resistance to frequency-selective channel conditions such as fading. For example, when a part of the channel bandwidth fades, frequency interleaving ensures that the bit errors that would result from those subcarriers in the faded part of the bandwidth are spread out in the bit-stream rather than being concentrated. Similarly, time interleaving ensures that bits that are originally close together in the bit-stream are transmitted far apart in time, thus mitigating against severe fading as would happen when travelling at high speed.

However, time interleaving is of little benefit in slowly fading channels, such as for stationary reception, and frequency interleaving offers little to no benefit for narrowband channels that suffer from flat-fading (where the whole channel bandwidth fades at the same time).

The reason why interleaving is used on OFDM is to attempt to spread the errors out in the bit-stream that is presented to the error correction decoder, because when such decoders are presented with a high concentration of errors the decoder is unable to correct all the bit errors, and a burst of uncorrected errors occurs.

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, 2NCBPS. 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 (LSB) bits 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, just 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 rule,

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

The deinterleaver, 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,

.

* 1. **Forward Error Correction**

The Forward error correction (FEC) is Inner convolutional coding. 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 2. The bit denoted as "A" shall be output from the encoder before the bit denoted as "B". The summation operation presented in Figure 2 is a modulo-2 summation, i.e., an XOR operation. 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 3. Decoding by the Viterbi algorithm is recommended.

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**Figure 2 Convolution encoder (133,171)**

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Figure 3 Puncturing (bit stealing) algorithm

* 1. **OFDM Modulator**

The real time-domain OFDM signal, generated at the PHY layer, is used to modulate the light emitting device (a light emitting diode (LED) or a laser diode (LD)), which serves as the transmitter front-end. The modulation is conducted only within the active operational range of the device. In this range, the electrical signal and the light output signal can only be positive at all times. The conventional approach for modulating the LED active range with an OFDM signal shall be to set a positive operating point, around which the bipolar OFDM signal can be realized. Figure 4 illustrates this principle. The positive bias can be introduced as part of the analog front-end (in the case of AC-coupled LED drivers) or as part of the information signal (in case of DC-coupled drivers). This approach is known as DC-biased optical OFDM (DCO-OFDM).

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Figure 4 DC-biased optical OFDM (DCO-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 inverse discrete Fourier transform is implemented with an IFFT algorithm. The DFT/IDFT size in the current PHY mode is fixed to 64. The DC subcarrier (subcarrier index 0 in the IFFT operation) and the 180-degree subcarrier (subcarrier index 32 in the IFFT operation) are set to 0. The information and pilot symbols with coefficients 1 to 26 are mapped to IFFT inputs 3 to 28, while the Hermitian symmetry symbols are mapped onto IFFT inputs 35 to 61. The high-frequency subcarriers, at inputs 29 to 34, form a guard interval and are set to zero. The low-frequency subcarriers, at inputs 0-2 and 62-63, are set to zero in order to avoid possible low-frequency distortion in the system due to baseline wandering and background light interference. The mapping is illustrated in Figure 5.

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Figure 5 IDFT realization by means of an IFFT algorithm

An optional alternative modulation approach is the enhanced unipolar OFDM (eU-OFDM). It constitutes of a digital processing algorithm, which can turn the bipolar OFDM signal into a strictly unipolar information signal without the addition of an energy intensive DC component that carries no additional information.

The transmitter signals to the receiver the new transmission PHY mode using the eU and STR bits in the advanced modulation PHY header. For compliance purposes, the PLCP preamble and the PHY headers are encoded in a DCO-OFDM fashion. Following the four BPSK OFDM symbols containing the PHY header, as well as the reference symbols when applicable, the data field is encoded in an eU-OFDM fashion. The eU-OFDM algorithm works as follows.

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Figure 6 Enhanced Unipolar OFDM (eU-OFDM)

For a single eU-OFDM stream, specified by STR = '0', two consecutive copies of every OFDM symbol are generated. The polarity of the samples in the second copy is inverted, and finally, all negative samples in the resulting time-domain signal are set to zero. The resulting positive signal can be used to modulate the transmitter. The concept is illustrated in Figure 6.

For two eU-OFDM streams cases, every three OFDM symbols are grouped into an eU-OFDM block, where the first two symbols are assigned to data stream 1 (St1) and the remaining one symbol is assigned to data stream 2 (St2). The two symbols in St1 are modulated using the algorithm described for STR='0'. The symbol in St2 is modulated in a similar manner, but instead of two copies, four consecutive copies are created for the OFDM symbol in St2, where the first two copies are kept unchanged, while the polarity of the samples in the next two copies is inverted. Following this procedure, all negative samples in both St1 and St2 are removed, and the two signals are summed. Any time domain oversampling and pulse shaping should be done after the removal of the negative samples. If done before the negative samples are removed, the oversampling and pulse shaping should also be performed at the receiver side during the signal re-modulation process required for the data recovery as explained in the RX algorithm. The resulting positive signal can be used to modulate the transmitter. The concept is presented in Figure 7.

For three eU-OFDM streams, every seven OFDM symbols are grouped into an eU-OFDM block, where the first four symbols are assigned to data stream 1 (St1), the next 2 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-stream case. The symbol in St3 is modulated in a similar manner, however, eight consecutive copies of that symbol are generated, where the first four copies are left unchanged, while the polarity of the samples in the following four copies is reversed. Following this procedure, all negative samples in St1, St2 and St3 are removed. Any time-domain oversampling and pulse shaping should be done after the removal of the negative samples. If done before the negative samples are removed, the oversampling and pulse shaping should also be performed at the receiver side during the signal re-modulation process required for the data recovery as explained in the RX algorithm. The signals in the three streams are summed and the resulting positive signal can be used to modulate the transmitter. The concept is presented in Figure 8.

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Figure 7 Unipolar OFDM generation (1 stream)

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Figure 8 Unipolar OFDM generation (2 streams)

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Figure 9 Unipolar OFDM generation (3 streams)

For four eU-OFDM streams, indicated by STR = '1', every fifteen OFDM symbols are grouped into an eU-OFDM block, where 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 1, 2 or 3 streams. In the second stream, four consecutives 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 2 streams and for 3 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 2 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 At this point, all negative samples in the four streams are removed and the signals from the three streams are added together. Any oversampling and pulse shaping should be done after the removal of the negative samples. If done before the negative samples are removed, the oversampling and pulse shaping should also be performed at the receiver side during the signal re-modulation process required for the data recovery as explained in the RX algorithm. The resulting positive signal can be used to modulate the transmitter.

* 1. **PPDU format**

Preamble

Channel estimation

SHR

PHY header

HCS

Optional Fields

PHR

Payload

PHY payload

**Figure 10 PPDU format for Low Bandwidth OFDM PHY**

The LB-PHY uses the PPDU format shown in ***Figure 10***. It consists of a synchronization header (SHR), physical layer header (PHR) and PHY payload.

**1.2 Transmission**

**1.2.1 Synchronization Header (SHR)**

**1.2.1.1 Preamble**

The PHY Preamble field is used for packet detection and synchronization. Preamble enables the identification of the existence of a transmission, as well as automatic gain control (AGC). It consists of Pseudo Noise (PN) 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 PN training sequences.

Step 1: Select two 20-bit PN sequences:

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 PN sequences (i.e., ).

**1.2.1.2 Channel estimation**

Channel estimation field consists of two repetitions of a “Hermitian symmetric long training sequence” preceded by a guard interval (GI). The sequence in channel estimation field is a time domain sequence and does not have any channel coding or line coding.

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 contains the following values modulated on the subcarriers of two identical OFDM symbols (index 0 corresponds to the DC subcarrier modulation value):

The sequence is Hermitian symmetric in order to obtain a real time-domain signal after the IDFT. Hermitian symmetric sequence also has very good auto-correlation properties. In Figure 11, the channel estimation OFDM symbol is transmitted twice in two identical copies of the time-equivalent signal of the frequency-domain modulation sequence . The guard interval is a cyclic extension of this same time-domain signal and has a duration of 32 samples (twice the length of the typical cyclic extension for this PHY mode specification).

Figure 11 Timing parameters for the PHY control information (specification for 20 MHz)



Preamble

GI2

Estimation Symbol

Estimation Symbol

GI

GI

GI

GI

Basic Header 1

Basic Header 2

Adv. Mod. Header 1

Adv. Mod. Header 2

GI

GI

GI

MIMO RS N-3

MIMO RS N-2

MIMO RS N-1

GI

GI

GI

MIMO RS1

MIMO RS2

MIMO RS3

MIMO RS N

GI

MIMO support, MIMO reference symbols, Channel estimation

Signal Detection, Automatic Gain Control

Channel Estimation, Fine Synchronization

RATE, LENGTH, …

Adaptive Loading, Waveform, …

**1.2.2 Physical Layer Header (PHR)**

**1.2.2.1 PHY header**

The PHY header contains all information necessary for demodulating the subsequent frame payload. It is always encoded in 1/2 FEC rate BPSK modulation using DCO-OFDM.

Basic PHY header is compulsory for all frames. Advanced Modulation Header may be added after the basic PHY header which is indicated by the basic PHY header.

The basic header contains the minimum information required for demodulating the subsequent payload. In LB-PHY, the header includes information such as the constellation size, the FEC rate and the payload size. The basic header contains 24 bits and fits within 2 OFDM symbols of the current PHY mode. The basic PHY header defines the fields given in ***Table 2***.

|  |  |  |  |
| --- | --- | --- | --- |
| **Field** | **Octet** | **Bits** | **Description** |
| **RATE** | 0 | [2:0] | PHY type and data rates |
| **Reserved** | 0 | [3] | Reserved for future use |
| **PSDU length** | 0-1 | [14:4] | Length up to |
| **Advanced modulation header** | 1 | [15] | Indicating whether an Advanced Modulation Header is following the basic PHY header |
| **High-reliability control** | 2 | [0] | Indicating whether a high-reliability control is used |
| **Parity** | 2 | [1] | An even parity check bit for the information in bits 0 - 16 |
| **Tail** | 2 | [7:2] | 6 zero bits |

**Table 2 Fields in the basic PHY header**

The individual fields of the basic header are described as follows.

**RATE** consists of three bits and indicates the QAM constellation size and the FEC rate (achieved with the use of a convolutional encoder and puncturing) used for the subsequent payload. The values specified in Table 3 are valid for the RATE field. Data rates for different MCSs are provided based on OCRs. Table 3 lists example common selections of OCRs. The range of the available OCRs is [1, 32] MHz. The OCR can be obtained by dividing the available frequency by 8. The data rates for are times of the data rates for OCR 1MHz in the above table for each MCS accordingly.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **R0-R2** | **Modulation** | **FEC rate** | **Date rate (Mbps) (OCR 1 MHz)** | **Date rate (Mbps) (OCR 16 MHz)** | **Date rate (Mbps) (OCR 20 MHz)** | **Date rate (Mbps) (OCR 32 MHz)** |
| **000** | **BPSK** | **Inner CC(1/2)** | **0.3** | **4.8** | **6** | **9.6** |
| **001** | **Inner CC(3/4)** | **0.45** | **7.2** | **9** | **14.4** |
| **010** | **QPSK** | **Inner CC(1/2)** | **0.6** | **9.6** | **12** | **19.2** |
| **011** | **Inner CC(3/4)** | **0.9** | **14.4** | **18** | **28.8** |
| **100** | **16-QAM** | **Inner CC(1/2)** | **1.2** | **19.2** | **24** | **38.4** |
| **101** | **Inner CC(3/4)** | **1.8** | **28.8** | **36** | **57.6** |
| **110** | **64-QAM** | **Inner CC(2/3)** | **2.4** | **38.4** | **48** | **76.8** |
| **111** | **Inner CC(3/4)** | **2.7** | **43.2** | **54** | **86.4** |

Table 3 Valid RATE values

**Reserved** bit is reserved for introducing additional transmission rates in future modifications of the standard.

**PSDU length** scales from 0 up to *aMaxPHYFrameSize.* The 11-bit field indicates the size of the payload in octets. Hence, the size of the payload is between 0 and 2048 octets.

**Advanced Modulation Header** bit indicates whether an Advanced Modulation Header follows the basic PHY header.

“1” indicates: Advanced Modulation Header follows the basic PHY header.

“0” indicates: Advanced Modulation Header will not appear after the basic PHY header.

**High-reliability Control** bit indicates whether a high-reliability control header is added at the beginning of the payload.

“1” indicates: The payload starts with the high-reliability control header.

“0” indicates: The payload does not start with the high-reliability control header.

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

**Tail** consists of 6 bits which are set to 0 to complete the basic PHY header.

Advanced Modulation Header is encoded in separate OFDM frames from the basic PHY header. The advanced modulation header is also encoded using 1/2 FEC rate BPSK. The advanced modulation header is an optional field which contains the information necessary for demodulating the subsequent waveform. It contains information necessary to identify if adaptive bit and energy allocation is used. It also contains commands for the PHY necessary for estimating the channel quality indicators (CQIs), necessary for enabling adaptive bit and energy loading during the real-time operation of the system.

The advanced modulation header defines the fields given in ***Table 4***.

|  |  |  |  |
| --- | --- | --- | --- |
| **Field** | **Octet** | **Bits** | **Description** |
| **Adaptive** | 0 | [0] | Whether carriers are to be allocated dynamically |
| **CQI** | 0 | [1] | Indicate if CQIs should be calculated in the PHY for the current transmission frame |
| **eU-OFDM** | 0 | [2] | Indicate if payload is encoded using eU-OFDM |
| **STR** | 0 | [3] | Indicate the number of eU-OFDM streams superimposed in the signal encoding procedure |
| **Reserved** | 0 | [9:4] | Reserved for future use |
| **Relaying enabled** | 1 | [10] | Indicate if relaying should be performed for the current PHY frame |
| **Relaying mode** | 1 | [12:11] | Specify the mode of relaying operation to be performed |
| **MIMO enabled** | 1 | [13] | Indicate if a MIMO mode is enabled for the current PHY frame |
| **MIMO reference symbol** | 1 | [14] | Indicate format of the reference symbols used for CQI estimation |
| **Reserved bits** | 1-2 | [16:15] | Reserved for future use |
| **Parity** | 2 | [17] | An even parity check bit for the information in bits 0 - 16 |
| **Tail** | 2 | [23:18] | 6 zero bits |

**Table 4 Fields in the advanced modulation header**

The individual fields of the basic header are described as follows.

**Adaptive** bit indicates whether adaptive bit loading is used to encode the subsequent payload:

“1” indicates: Adaptive bit loading is used. In this case, the subsequent payload is encoded with the loading scheme which the receiving device has estimated and suggested to the transmitter using the feedback channels and negotiation procedures on the MAC sub-layer.

“0” indicates: Adaptive bit loading is not used. In this case, the subsequent payload is encoded with the default loading scheme and the rate specified in the basic PHY header.

LB-PHY does not support adaptive bit loading. If any PHY which does not support bit loading receives a packet with a “1” in this bit, it ignores the packet as it will not be able to demodulate.

**CQI** bit indicates whether the CQIs should be calculated in the PHY for the current transmission frame.

“1” indicates: the CQIs should be estimated

“0” indicates: the CQIs should not be estimated

The channel estimation symbols preceding the PHY header are used for the estimation of the CQIs if the MIMO mode is not enabled. If MIMO mode is enabled, the MIMO reference symbols used for CQI estimation is further defined in MIMO RS field in the advanced modulation header.

Upon estimation of the CQIs, the PHY conveys the results to the MAC using a predefined PHY service primitive. The calculation of the bit and power allocation scheme as well as the necessary exchange for updating the bit and power allocation scheme at the transmitter and receiver are handled at the MAC layer.

**eU-OFDM** indicates whether the payload field is encoded using eU-OFDM.

“1” indicates: the payload is encoded using eU-OFDM.

“0” indicates: the payload is not encoded using eU-OFDM.

Note that the use of this waveform can be negotiated in advance using control/management frames. Furthermore, the use of eU-OFDM encoding does not prohibit the use of any other waveforms such as RPO-OFDM.

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

“0” indicates: the number of eU-OFDM streams superimposed in the signal encoding procedure is 1.

“1” indicates: the number of eU-OFDM streams superimposed in the signal encoding procedure is 4.

**Reserved bits** are reserved for future use.

**Relaying mode** specifies the type of relaying mode that should be performed.

“00” specifies: Relaying and duplexing mode is FD-AF.

“01” specifies: Relaying and duplexing mode is FD-DF.

“10” specifies: Relaying and duplexing mode is HD-AF.

“11” specifies: Relaying and duplexing mode is HD-DF.

**MIMO enabled** bit indicates whether a MIMO mode is enabled for the current PHY frame.

“1” indicates: MIMO mode is enabled and the subsequent payload is encoded using the MIMO scheme already negotiated between the transmitter and the receiver.

“0” indicates: MIMO mode is not enabled and the subsequent payload is encoded using the SISO scheme specified by the parameters in the basic PHY header and the advanced modulation header.

**MIMO Reference Symbols** Format bit indicates the format of the reference symbols used for CQI estimation.

“0” indicates: MIMO Reference Symbols Format I is used.

“1” indicates: MIMO Reference Symbols Format II is use

The two MIMO reference symbols formats are specified in 1.2.2.3.

**Reserved** bit is reserved for future use.

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

**Tail** consists of 6 bits which are set to 0 to complete the advanced modulation header.

**1.2.2.2 HCS**

The header check sequence (HCS) is not used in LB-PHY.

**1.2.2.3. Optional fields**

Optional fields contain reference symbols for multiple-input multiple-output (MIMO) channel estimation. For MIMO RS, repetitions, FEC, line coding and HCS do not apply. The optional fields include MIMO Reference Symbols (RS).

MIMO reference symbols constitute OFDM frames (or the time-frame equivalent of OFDM frames), where is the number of MIMO channels. The MIMO RS formats are described as follows.

**MIMO Reference Symbols Format I**

For each MIMO transmitter, only one OFDM frame interval is set to the desired channel estimation sequence (CES). All other intervals are set to zero. Thus, the CES transmission intervals never coincide with any other transmitters. Hence, the MIMO reference symbols for the different transmitters are orthogonal to each other. The format is presented in Figure 12.



Figure 12 MIMO RS format I

**MIMO Reference Symbols Format II**

For each MIMO transmitter, every frame interval is set to the desired CES. In addition, the CESs for each transmitter are modified by adjusting the polarity of the individual CES sequences according to a pre-determined set of Walsh sequences, where a value of '1' in the Walsh sequence corresponds to an unmodified CES sequence while a value of '-1' corresponds to a CES sequence with reverse polarity. The format is presented in Figure 13. The CES sequences in white are left unmodified, while the CES sequences in gray are multiplied by -1.



Figure 13 MIMO RS format II

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

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

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

As a general rule, the Walsh sequences for a MIMO configuration with transmitters () correspond to the rows of the matrix :

**1.2.2.4 PHY header encoding**

The PHY headers (both the basic header and the advanced modulation header) shall be encoded using 1/2 rate FEC coding (no puncturing is used). The encoded bits shall also be mapped to a BPSK symbol constellation.

**1.2.3 PHY payload**

Payload is transmitted at one of the supported data rates. Payload consists of service, length of packet, PSDU, tail, and pad fields. If indicated in the basic PHY leader, payload may also include a high-reliability control field.

The payload defines the fields given in Table 5.

|  |  |  |  |
| --- | --- | --- | --- |
| **Field** | **Octet** | **Bits** | **Description** |
| **High-reliability Control** | 0-5 | [47:0] | Indication of polling and acknowledgement information |
| **Service** | 6-7 | [15:0] | Service bits for scrambler initialization |
| **Length of packet** | 8-9 | [15:0] | Indicates the length of this packet |
| **PSDU** | variable | variable | Indicates the length of the PHY frame |
| **Tail** | variable | variable | 6 zero bits |
| **Pad** | variable | variable | Pad bits are appended to payload field as to ensure the number of bits in the payload field to be a multiple of . |

Table 5 Fields in payload

The individual fields of the payload are described as follows.

**1.2.3.1 High-reliability Control**

Robust transmission of the polling and acknowledgement information ensures avoiding a lot of unnecessary retransmissions. Furthermore, when this information is encoded separately from the rest of the payload, errors in the payload (especially for long payloads) which cause the packet to be discarded (and retransmitted) do not affect the polling and acknowledgement mechanism. The MAC header is encoded using the lowest data-rate (most robust) modulation format 1/2 FEC rate BPSK separately from the data payload.

The high-reliability control defines the subfields given in Table 6.

|  |  |  |  |
| --- | --- | --- | --- |
| **Subfield** | **Octet** | **Bits** | **Description** |
| **Reserved** | 0 | [1:0] | Reserved for future use |
| **Polled device** | 0 | [6:2] | Indication of the device to be polled (by coordinator only) |
| **Next device to poll** | 0-1 | [11:7] | Indication of the next device to be polled (by coordinator only) |
| **Device to acknowledge** | 1-2 | [16:12] | Indicates which device is to be acknowledged by this packet |
| **Buffer status reporting** | 2 | [17] | Indicates the current device has more data waiting for transmission (by devices only) |
| **Sequence number** | 2-3 | [29:18] | Sequence number of the packet to ACK |
| **Payload ACK** | 3 | [30] | Indicates that this is to acknowledge a payload |
| **Beacon ACK** | 3 | [31] | Indicates that this is to acknowledge a beacon |
| **CRC** | 4 | [7:0] | 8 bits cyclic redundancy check (CRC) for pervious sub-fields |
| **Reserved** | 5 | [1:0] | Reserved for future use |
| **Tail** | 6 | [7:2] | 6 zero bits |

Table 6 Fields in high-reliability control

The individual subfields of the high-reliability control are described as follows.

**Reserved** fieldconsists of two bits which are reserved for future use.

**Polled device** subfield specifies the device which is being polled by the coordinator in the downlink. On the uplink, these bits are left unspecified.

**Next device to poll** subfield specifies the next device which is being polled by the coordinator in the downlink. On the uplink, these bits are left unspecified.

**Device to acknowledge** subfield specifies the device which is being acknowledged by the packet.

**Buffer status reporting** subfield indicates that the current device has more date in the queue waiting for transmission. The bit is only used by devices. For coordinators, the bit is unspecified.

**Sequence number** consists of twelve bits which specifies the sequence number of the packet that is being acknowledged.

**Payload ACK** indicates that this acknowledgement is for a payload.

**Beacon ACK** indicates that this acknowledgement is for a beacon.

**CRC** consists of 8 bits CRC for pervious sub-fields.

**Reserved** subfield includes 2 bits reserved for future use.

**Tail** subfield consists of 6 bits of zeros to complete the high-reliability control.

**1.2.3.2 Service subfield**

The Service subfield has 16 bits, which shall be denoted as bits 0-15. The bit 0 shall be transmitted first in time. The bits from 0-6 of the SERVICE subfield, which are transmitted first, are set to zeros and are used estimate the initial state of the transmitter scrambler and to synchronize the descrambler in the receiver. The remaining 9 bits (7-15) of the SERVICE subfield shall be reserved for future use. All reserved bits shall be set to 0. The bit allocation is demonstrated in Figure 14.

****

Figure 14 Service field bit allocation

**1.2.3.3 Length of packet subfield**

The field specifies the length of the packet in the payload. With such accurate information, transmission and processing efficiency is improved because it will not require the TX and RX to reset First In First Out (FIFO) queues after each packet.

**1.2.3.4 PSDU field**

The PSDU field has a variable length and carries the data of the PHY frame. If eU-OFDM is enabled the Data shall be encoded in an eU-OFDM fashion.

**1.2.3.5 Tail field**

The PPDU Tail field shall be 6 bits of zeros, which are required to complete the payload.

**1.2.3.6 Padding Bits**

The number of bits in the payload field shall be a multiple of , the number of coded bits in an OFDM symbol (24, 48, 96, or 144 bits). To achieve this, the length of the message is extended so that it becomes a multiple of , the number of data bits per OFDM symbol. At least 6 bits are appended to the message, in order to accommodate the Tail bits. The number of OFDM symbols, ; the number of bits in the payload field, ; and the number of pad bits, , are computed from the length of the PSDU (LENGTH) as follows:

The appended pad bits are set to 0 and are subsequently scrambled with the rest of the bits in the payload.

**1.2.3.7 PHY DATA scrambler and descrambler**

The DATA field shall be scrambled with a length-127 PPDU-synchronous scrambler. The octets of the PSDU are placed in the transmit serial bit stream, bit 0 first and bit 7 last. The PPDU synchronous scrambler uses the generator polynomial as follows and is illustrated in Figure 15,

A close up of a clock

Description generated with high confidence

Figure 15 PHY DATA scrambler

The 127-bit sequence generated repeatedly by the scrambler shall be (leftmost used first), 00001110 11110010 11001001 00000010 00100110 00101110 10110110 00001100 11010100 11100111 10110100 00101010 11111010 01010001 10111000 1111111, when the all 1s initial state is used. The same scrambler is used to scramble transmit data and to descramble receive data.

**References**

**Annex**