**­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 LiFi applications with data rates in the tens of Mb/s using OFDM modulation. OFDM in the current specification enables a highly adaptive modular implementation, which supports both a high-efficiency PHY mode designed to enable optimal utilization of the low-bandwidth resources (up to 40 MHz of single-sided bandwidth) as well as a low-complexity PHY mode designed to enable high energy efficiency in mobile applications. LB-PHY targets an efficient utilisation of the optical bandwidth as well as enhancing transmission reliability. This approach serves applications where high data rates are needed, e.g. in the downlink. For modulation of the LED, multiple optical clock rates (OCR) are used. Furthermore, the specification enables the adaptive and modular introduction of energy-efficient waveforms such as enhanced unipolar OFDM (eU-OFDM), performance enhancing waveforms such as single-carrier FDMA (SC-FDMA) and waveforms designed for improved illumination control such as reverse polarity optical OFDM (RPO-OFDM). In addition, the specification supports the application of adaptive bit and energy loading techniques as well as multiple-input multiple-output (MIMO) techniques which can leverage the additional communication capacity of multiple light sources as well as the additional communication capacity introduced by the utilization of different optical wavelengths and light polarization for communication. The PHY specification supports relaying mechanisms for the cases when dedicated relay terminals are available. A DC-biased optical OFDM (DCO-OFDM) waveform is the basis and the foundation of all concepts, which are specified as optional features and can be applied in a nonconflicting manner.

* 1. **PPDU format**

Preamble

Channel estimation

SHR

PHY header

HCS

Optional Fields

PHR

Payload

PHY payload

**Figure 1 PPDU format for Low Bandwidth OFDM PHY**

The LB-PHY uses the PPDU format shown in **Figure *1***. 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:

$pn\\_seq\_{0} = 20'b01001011000001110111$

$$pn\\_seq\_{1} = 20'b01101100111101010000$$

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., $pn\\_seq\_{0} and pn\\_seq\_{1}$).

**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):

$$E\_{0 to 63} = \{0,0,0,0,-1,1,-1,-1,1,1,-1,-1,-1,-1,-1,1,-1,1,1,1,-1,-1,-1,1,1,$$

$$-1,1,-1,1,1,0,0,0,0,0,1,1,-1,1,-1,1,1,-1,-1,-1,1,1,1,-1,1,-1,-1,-1,-1,-1,$$

$$1,1,-1,-1,1,-1,0,0,0\}$$

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 2, the channel estimation OFDM symbol is transmitted twice in two identical copies of the time-equivalent signal of the frequency-domain modulation sequence $E\_{0 to 63}$. The guard interval $GI2$ 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 2 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 *1***.

|  |  |  |  |
| --- | --- | --- | --- |
| **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 $aMaxPHYFrameSize$ |
| **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 1 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 2 are valid for the RATE field. Data rates for different MCSs are provided based on OCRs. Table 2 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 $OCR\_{m}$ are $OCR\_{m}$ 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 2 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 *3***.

|  |  |  |  |
| --- | --- | --- | --- |
| **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 |
| **SC-FDMA** | 0 | [4] | Indicate if payload field is encoded using SC-FDMA |
| **DFT** | 0-1 | [9:5] | DFT size used in the SC-FDMA pre-coding procedure |
| **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 3 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 SC-FDMA or 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.

**~~SC-FDMA~~** ~~indicates whether the payload field is encoded using SC-FDMA.~~

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

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

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

**DFT** specifies the DFT size used in the SC-FDMA pre-coding procedure. As only 24 subcarriers are modulated with unique data, the DFT size is a number between 1 and 24.

Relaying enabled indicates whether relaying should be performed for the current PHY frame.

“1” indicates: Relaying should be performed for the current PHY frame.

“0” indicates: Relaying should not be performed for the current PHY frame.

**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 $N\_{RS}$ MIMO Reference Symbols (RS).

MIMO reference symbols constitute $N\_{MIMO}$ OFDM frames (or the time-frame equivalent of $N\_{MIMO}$ OFDM frames), where $N\_{MIMO}$ 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 3.



Figure 3 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 4. The CES sequences in white are left unmodified, while the CES sequences in gray are multiplied by -1.



Figure 4 MIMO RS format II

The Walsh sequences for a MIMO configuration with two transmitters ($N\_{MIMO}=2$) correspond to the rows of the matrix $W^{2}MIMO$:

$$\left[\begin{matrix}1&1\\1&-1\end{matrix}\right]$$

The Walsh sequences for a MIMO configuration with four transmitters ($N\_{MIMO}=4$) correspond to the rows of the matrix $W^{4}MIMO$:

$$\left[\begin{array}{c}\begin{matrix}1&1\\1&-1\end{matrix}\begin{matrix} 1&1\\ 1&-1\end{matrix}\\\begin{matrix}1&1\\1&-1\end{matrix} \begin{matrix}-1&-1\\-1&1\end{matrix}\end{array}\right]$$

The Walsh sequences for a MIMO configuration with eight transmitters ($N\_{MIMO}=8$) correspond to the rows of the matrix $W^{8}MIMO$:

$$\left[\begin{array}{c}\begin{array}{c}\begin{matrix}1&1\\1&-1\end{matrix}\begin{matrix} 1&1\\ 1&-1\end{matrix}\\\begin{matrix}1&1\\1&-1\end{matrix} \begin{matrix}-1&-1\\ -1&1\end{matrix}\end{array}\begin{array}{c}\begin{matrix}1&1\\1&-1\end{matrix}\begin{matrix} 1&1\\ 1&-1\end{matrix}\\ \begin{matrix} 1&1\\ 1&-1\end{matrix} \begin{matrix}-1&-1\\-1&1\end{matrix}\end{array}\\\begin{array}{c}\begin{matrix}1&1\\1&-1\end{matrix} \begin{matrix} 1&1\\ 1&-1\end{matrix}\\\begin{matrix}1&1\\1&-1\end{matrix} \begin{matrix}-1&-1\\-1&1\end{matrix}\end{array}\begin{array}{c} \begin{matrix}-1&-1\\-1&1\end{matrix} \begin{matrix}-1&-1\\- 1&1\end{matrix}\\\begin{matrix} -1&-1\\ -1&1\end{matrix} \begin{matrix}1&1\\1&-1\end{matrix}\end{array}\end{array}\right]$$

As a general rule, the Walsh sequences for a MIMO configuration with $2^{k}$ transmitters ($N\_{MIMO}=2^{k}$) correspond to the rows of the matrix $W^{2^{k}}MIMO$:

$$\left[\begin{matrix}W^{2^{k-1}}MIMO&W^{2^{k-1}}MIMO\\W^{2^{k-1}}MIMO&-W^{2^{k-1}}MIMO\end{matrix}\right]$$

**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 4.

|  |  |  |  |
| --- | --- | --- | --- |
| **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 $N\_{CBPS}$. |

Table 4 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 5.

|  |  |  |  |
| --- | --- | --- | --- |
| **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 5 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 5.

****

Figure 5 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 $N\_{CBPS}$, 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 $N\_{DBPS}$, 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, $N\_{SYM}$; the number of bits in the payload field, $N\_{PAYLOAD}$; and the number of pad bits, $N\_{PAD}$, are computed from the length of the PSDU (LENGTH) as follows:

$$N\_{SYM}=\left⌈\frac{16+8×LENGTH+6}{N\_{DBPS}}\right⌉$$

$$N\_{PAYLOAD}=N\_{SYM}×N\_{DBPS}$$

$$N\_{PAD}=N\_{PAYLOAD}-(16+8×LENGTH+6)$$

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

**References**

**Annex**