**IEEE P802.15**

**Wireless Personal Area Networks**

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| Abstract | [Proposal for pulsed modulation PHY in 802.15.13]  |
| Purpose | [Inform TG13 about most recent work.] |
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1. **Pulsed Modulation PHY**

The Pulsed Modulation PHY enables moderate data rate from 1 Mbit/s up to some 100 Mbit/s. The main approach is to achieve high data rates by using a high optical clock rate while keeping spectral efficiency low. This approach offers significantly higher reach where power efficiency is an important factor, e.g. in uplink scenarios, industrial wireless and in the Internet of Things (IoT). PAM modulation with variable rates is used, together with 8B10B line coding and a Reed-Solomon forward error correction (FEC) scheme with high code rate. The numerology is defined in Table 1. Controlled by higher layers, the PM PHY includes means to adapt the data rate to varying channel conditions i) by varying the optical clock rates and ii) by varying the modulation and coding scheme. In Table 1, only i) is considered.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Opt. clock rate /MHz** | **Opt. clockcycle/ns** | **Tseq/ns** | **TCP/ns** | **Nseq/optical clock cycles** | **NCP/optical clock cycles** | **MCS** | **Data rate/****Mbit/s** | **Channel estimation sequence (Appendix** |
| 6.25 | 160 | 5120 | 160  | 32 | 1  | 2-PAM8B10BRS(256,248) | 4.7 | A32 |
| 12.5 | 80 | 64 | 2  | 9.4 | A64 |
| 25 | 40 | 128 | 4  | 19 | A128 |
| 50 | 20 | 256 | 8  | 38 | A256 |
| 100 | 10 | 512 | 16  | 75 | A512 |
| 200 | 5 | 1024 | 32 | 150 | A1024 |

**Table 1 Numerology for Pulsed Modulation PHY**

Optical clock rates (OCR) in Table 1 are obtained from a common reference clock of 100 MHz which is available from low-cost off-the-shelf crystal oscillators by dividing the clock as 100 MHz/n where n=1/2, 1…5. The reference clock can also be obtained via Ethernet using the precision time protocol (PTP) defined in IEEE std. 1588v2. Jitter can be improved by synchronous Ethernet (synchE) defined in ITU-T rec. G.8262.

* 1. **PPDU format**

Preamble

Channel estimation

SHR

PHY header

HCS

Optional Fields

PHR

PPDU

PHY payload

**Figure 1 PPDU format for Pulsed Modulation PHY**

The PM PHY uses the PPDU format shown in Figure 1. It consists of a synchronization header (SHR), physical layer header (PHR) and PHY payload (PPDU). Fields are specified in the following sub-clauses.

**1.2 Transmission**

**1.2.1 Synchronization Header (SHR)**

**1.2.1.1 Preamble**

The Preamble enables Schmidl-Cox autocorrelation [1-4] to achieve time synchronization using a correlation window size of 192. As a base sequence **A**64, a specific pseudo-noise sequence of length 64 is used, see Appendix 1).

In the preamble, the base sequence **A**64 is repeated six times yielding a total sequence length of 384. Each base sequence is multiplied with positive or negative sign as given below which is known to create a sharper peak after the autocorrelation, compared to a double word of the same total sequence length [4].

The total preamble reads **P**384 = [**A**64 **A**64 **-A**64 **A**64 **-A**64 **-A**64].

The preamble is finally passed through a 2-PAM Modulator.

**1.2.1.2 Channel estimation**

The channel estimation sequence enables block-wise frequency-domain equalization (FDE). The block consists of two parts, a base sequence and a cyclic prefix (CP). Measured in time units, the durations of both, the base sequence Tseq and the cyclic prefix TCP are maintained, independent of the optical clock rate. Also without using FDE, the CP is transmitted. Consistent block duration allows mixed operation of links with different optical clock rates in the same superframe. By increasing the OCR, the number of optical clock cycles for the sequence and for the CP, i.e. Nseq and NCP, respectively, increase proportionally, see Table 1.

As channel estimation sequence, a specific pseudo-noise sequence **A**N given in Appendix 1) of length N=2k (k=5…11) is used, depending on the OCR, so that N=Nseq (see Table 1).

The channel estimation sequence is finally passed through a 2-PAM Modulator.

**1.2.2 Physical Layer Header (PHR)**

**1.2.2.1 PHY header**

The PHY layer header has a fixed length and contains frame type (Probe or Transport) and the length of the PSDU. The PHY header defines the fields given in Table 2.

|  |  |  |  |
| --- | --- | --- | --- |
| **Field** | **Octet** | **Bits** | **Description** |
| FT | 0 | [7:0] | Frame type |
| PSDU\_length | 1-2 | [15:0] | Length of PSDU in optical clock cycles |

**Table 2 PHY header**

FT defines the frame types

FT=0 Transport frame (used in MAC e.g. for Data, RTS, CTS, ACK, Feedback, Control)

FT=1 Probe frame

FT>1 Reserved

The PSDU length scales from 0 up to *aMaxPHYFrameSize.*

**1.2.2.2 HCS**

The HCS uses CRC-16 as defined in Annex C. The HCS bits shall be processed in the transmitted order. The registers shall be initialized to all ones.

**1.2.2.3 Optional fields**

Presence and structure of optional fields depend on the FT defined in the beginning of the PHY header. If **FT=0** (transport frame), optional fields provide descriptors for the modulation and coding scheme (MCS) used, for implicit reference sequences (IRS) and the IRS themselves. IRS enable measurements of the effective channel matrix including the effect of the precoder for single stream or multiple streams transmitted in parallel. The effective channel matrix allows demodulation of data and higher layer control information.

|  |  |  |  |
| --- | --- | --- | --- |
| **Field** | **Octet** | **Bits** | **Description** |
| MCS\_vector | 3-6 | [31:0] | Modulation and Coding Vector for PSDU |
| IRS\_type | 7 | [7:0] | Type of IRS |
| NIRS | 8 | [7:0] | Number of IRS |
| IRS | n. a. | n. a. | Block of IRS |

**Table 3 Optional fields for FT=0.**

The MCS\_vector defines the used modulation and coding schemes, being a number for single-stream transmission and a vector for spatial multiplexing with per-stream MCS adaptation. MCS adaptation is due to the MAC Layer. Definition of MCS needs 8 bits per stream, see Table 4.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Field** | **Octet** | **Bits** |  | **Values** |
| Stream 1 | 3 | [0] | Line coding | 0:8B10B, 1:HCM |
| [3:1] | Modulation | 0:2-PAM1:4-PAM2:8-PAM3:16-PAM>3: reserved |
| [7:4] | NHCM | 0: NHCM=01: NHCM=1…15: NHCM=15 |
| Stream 2-4 | 4-6 | [31:8] | … | … |

**Table 4: Descriptor for the MCS vector.**

IRS type defines the use of time- or frequency-domain IRS. Time-domain IRSs typically apply for transmission without FDE at lower optical clock rates. They are also sufficient for single-stream transmission. Frequency-domain IRSs enable transmission at higher OCR using FDE. Moreover, they allow orthogonal transmission and detection of IRSs for multiple streams in the frequency domain.

If **FT=1** (probe frame), optional fields provide a time reference, descriptors for explicit reference sequences (ERS) and the ERS themselves. ERS enable measurement of the direct channel matrix from individual transmitters to individual receivers. The most important role of a probe frame is the beacon sent at the beginning of a superframe.

|  |  |  |  |
| --- | --- | --- | --- |
| **Field** | **Octet** | **Bits** | **Description** |
| Time\_stamp | 3-6 | [31:0] | Start of probe frame, 10 ns time resolution  |
| ERS\_type | 7 | [7:0] | Type of ERS |
| NERS | 8 | [7:0] | Number of ERS |
| ERS | n. a.  | n. a. | Block of ERS |

**Table 5 Optional fields for FT=1.**

ERS type defines the use of time- or frequency-domain ERS. Time-domain ERSs typically apply for transmission without FDE at lower OCR and using single or multiple transmitters. Frequency-domain ERS enable transmission at higher optical clock rates when using FDE and multiple transmitters.

IRS and ERS are constructed following the same basic principles. As IRS and ERS are reference signals, no repetitions, no FEC and no line coding apply to them.

***1.2.2.3.1. Time-domain RS***

The time-domain RS for the ith data stream/transmitter in case of IRS/ERS, respectively, is constructed by bit-wise logical XOR operation of the base sequence **A**N given in the Appendix 1), where N=Nseq according to the numerology in Tabl*e* 1, and the ith row of the NxN Hadamard matrix **H**k obtained as follows



where k=1…K and N=2K. Note that the sequence in the first row of **H**k contains a sequence with all ones reproducing the base sequence for the first stream or transmitter. All pairs of sequences in **H**k are mutually orthogonal, using bit-wise multiplication and summation over j=1…N. The XOR operation with **A**N does not change orthogonality of sequences but improves cross-correlation properties which is beneficial in case of multi-path [5, 6].

***1.2.2.3.2. Frequency-domain RS***

The frequency-domain RS for the ith data stream or transmitter use the base sequence **A**N given in the Appendix 1), where N=Nseq according to the numerology in Table 1. Frequency-domain RSs are a set of NRS OFDM symbols [7]. A specific comb of subcarriers in the frequency domain identifies a particular stream or optical frontend. Comb spacing *Δ* is defined by higher layers taking the fundamental relation

*Δ≤Nseq/NCP*

into account. The definition of *Δ* is conveyed to the receiver in the variables ERS\_type and IRS\_type. There are

*Ncomb*=*Nseq / Δ*

non-zerosignals (tines) in the comb. The base sequence AN where *N=Ncomb* yield an appropriate definition of the signals on tines yielding low peak-to-average power ratio in the time domain.

For the first stream/transmitter, the comb starts at the first subcarrier following the DC subcarrier (being excluded from frequency-domain transmission in general). By using a single RS, up to Δ streams/transmitters could be identified. This is achieved by a cyclic shift of the comb by an integer number Nshift=0…Δ-1 of subcarriers, which makes RS orthogonal in the frequency domain. However, higher layers shall reserve the shift Nshift = Δ-1 for noise estimation at the receiver. Any subset of streams or transmitters being smaller than Δ-1 can be identified by a single RS. When using more than Δ-1 streams or transmitters, one must add more RSs. Higher layers shall indicate this by variables Δ and NRS, where index RS means IRS and ERS, accordingly. In order to keep RSs for multiple subsets of streams/transmitters orthogonal to each other, the mth RS can be obtained by multiplication of the appropriate RS with the respective elements from the mth row of the MxM Hadamard matrix **H**k identifying the mth set of RSs. **H**k is obtained as follows

,

where k=1…K and M=2K=NRS is defined by higher layers.

**1.2.3. Header encoding and modulation**

**1.2.3.1 General**

The transmitter structure in Figure 2 is used for the header. Scrambling is only used in the coordinated topology to randomize uncoordinated interference. For enhanced error protection, the header is repeated 3 times. Header encoding uses RS(36,24) code as defined below. This particular order of line and channel coding achieves the lowest error rates. However, in this way only the systematic part of the binary output code word (24 bits) is well balanced. For maintaining a constant average light output for the entire sequence, also the redundant part of the binary code word (36-24=12 bits) has to be passed through 8B10B line encoder. Both parts are concatenated in a multiplexer and passed through the bit-to-symbol mapper for 2-PAM modulation. Finally, a spatial pre-coder selects what transmitters will sent out the header and how.



**Figure 2 Transmitter Structure for the header.**

**1.2.3.2 Scrambler**

For optional scrambling, a pseudo-random binary sequence (PRBS) is used being characteristic for a given data stream. A data stream can be transmitted from a cluster of one or more adjacent coordinators transmitting the same signal. The scrambling sequence is defined by higher layers and controlled by the master coordinator.

**1.2.3.3 Line Encoder**

In the header the line encoder always uses 8B10B code. For the 8B10B encoding, see ANSI/INCITS 373 and Appendix 3).

**1.2.3.4 RS(36,24) code**

For constructing the RS(36, 24) encoder and decoder, a symbol width of 10 is used, due to the output of 8B10B line coding. Accordingly, the generator polynomial x10+x3+1 is used. Scaling factor is 1 and generator start equal to 0.

**1.2.3.5 Bit-to-Symbol Mapping**

Bit-to-symbol mapping for the header is based on 2-Pulse Amplitude Modulation (PAM). For 2 levels, each input bit is mapped onto one symbol. The symbols are mapped to levels as {0, 1} to {0, 1}, respectively. A constant value of 0.5 is then subtracted to make the mapped output signal DC free. Setting the modulation amplitude and the bias of the LED is due to the analogue optical frontend.

**1.2.3.6 Spatial Precoder for the Header**

In general, the spatial precoder is a matrix-vector operation ***P****·****x*** operating symbol-wise when using time-domain RS and subcarrier-wise when using frequency-domain RS.

If FT=0 (transport frame), mathematically, the transmitter multiplies the 1x1 stream of header information symbols ***x***with the NERSx1 precoding vector ***P*** which contains ones for all active transmitters in a coordinated transmission cluster and zeros elsewhere. In this way all transmitters in the cluster broadcast the same header information (regional transmission). The master coordinator in the infrastructure network sends header information to all active transmitters in a coordinated transmission cluster. All transmitters send in a synchronous manner. How to realize synchronization of multiple distributed OWC transmitters is out of scope for this standard.

If FT=1 (probe frame), mathematically, the transmitter multiplies the 1x1 scalar stream of header symbols ***x*** with the NERSx1 vector ***P*** which contains all ones. In this way all transmitters broadcast the same header information (global transmission). The master coordinator in the infrastructure network sends the header information to all transmitters. All transmitters send in a synchronous manner. How to realize synchronization of multiple distributed OWC transmitters is out of scope for this standard.

**1.2.4 PHY payload**

**1.2.4.1 General**

The transmitter structure in Figure 3 applies to the payload, which besides data frames may also contain RTS, CTS, ACK, Feedback and Control frames defined by the MAC layer. Scrambling is only used in the coordinated topology to randomize uncoordinated interference. 8B10B line coding is then applied. For FEC, the payload uses RS(256,248) code with fixed code rate 248/256 as defined below. This particular order of line and channel coding achieves the lowest error rates. However, only the systematic part of the binary output code word (248 bits) is well balanced in this way. For maintaining a constant average light output for the entire sequence, also the redundant part of the binary code word (256-248=8 bits) has to be passed through 8B10B line encoder. Both parts are concatenated in a multiplexer and passed through the bit-to-symbol mapper where 2-PAM is commonly used. In combination with Hadamard Coded Modulation (HCM) other than the trivial mode HCM(1,1), no line coding is used and M-PAM with M≥2 may be used. By varying the parameter M for PAM and the number of used codes in HCM, the pulsed modulation PHY can adapt the data rate in several steps to time-varying channel conditions. The value of M and the configuration of HCM(i, N) for the payload are conveyed via the MCS vector. A spatial precoder selects finally what transmitters will sent out the payload and how.



**Figure 3 Transmitter Structure for the payload.**

**1.2.4.2 Scrambler**

For optional scrambling, a pseudo-random binary sequence (PRBS) is used being characteristic for a given data stream. A data stream can be transmitted from a cluster of one or more adjacent coordinators transmitting the same signal. The scrambling sequence is defined by higher layers and controlled by the master coordinator.

**1.2.4.3. RS(256,248) code**

For constructing the RS(256, 248) encoder and decoder, a symbol width of 10 is used, due to the output of 8B10B line coding. Accordingly, the generator polynomial x10+x3+1 is used. Scaling factor is 1 and generator start equal to 0.

**1.2.4.4 Line Encoder**

In combination with 2-PAM and HCM(1,1), the line encoder uses 8B10B. For the 8B10B encoding, see ANSI/INCITS 373 and [3]. In case HCM is used in other than the trivial HCM(1,1) mode, line coding is set to 1B1B, i.e. deactivated.

**1.2.4.5. Bit-to-Symbol Mapper**

The bit-to-symbol mapper is using PAM with 2 up to M levels. For 2 levels, each input bit is mapped in one symbol. The symbols are mapped to levels as {0, 1} to {0, 1}, respectively. With 4 levels, two consecutive bits are combined in a symbol. The symbols are mapped to levels as {00, 01, 10, 11} to {0, . , 1}, respectively. With arbitrary M, symbols map to signal levels as . Gray mapping for M-PAM for M=2… 16 is given in Appendix 2). A constant value of 0.5 is always subtracted to make the final mapper output DC free. Setting the modulation amplitude and the bias signal of the LED is due to the analogue optical frontend.

**1.2.4.6. Hadamard Coded Modulation**

Hadamard Coded Modulation (HCM) is an extension of the bit-to-symbol mapper and applied after PAM. Besides the opportunity to vary the data rate by using a variable number of spreading codes, HCM also removes the need for line coding. As shown in **Figure 4**, HCM, multiples a vector of N data symbols (where is a power of two) with a Hadamard matrix, what is also denoted as fast Walsh-Hadamard transform (FWHT). As described in [8], the HCM signal

is generated from the data sequence as

,

where is the binary Hadamard matrix of order [9], and is the complement of . The components of are assumed to be modulated using PAM.



**Figure 4 HCM encoder (left) and decoder (right)**

The DC part of HCM signals can be easily removed by setting the first component of () to zero and modulating only codewords of the Hadamard matrix with data symbols [8]. In this way, the average transmitted power is reduced by sending () instead of . Figure 5 shows an example of DC reduction. Reduced DC level counts per HCM symbol and its value can be different for each symbol. This idea makes transmitted signals orthogonal to DC bias at a overhead cost on data-rate.



**Figure 5 (a) A HCM signal, and (b) its corresponding DC reduced signal**

Table 6 lists overheads for different values of in comparison to 8B10 line encoding. Although higher values of N could enable lower data rates, synchronization gets lost at these correspondingly low SNR levels. In such cases it is better to reduce the OCR. As a consequence, HCM(NHCM,16) is used with variable number of codes transmitted in parallel NHCM=1…15.

|  |  |
| --- | --- |
| **HCM (N-1,**  | **Overhead [%]** |
| 2 | 50 |
| 4 | 25% |
| 8 | 12.5% |
| 16 | 6.25% |
| 32 | 3.2% |
| **8B10B** | 25% |

**Table 6 Over-head of HCM compared to 8B10B for different values of**

Table 7 lists possible transmission modes by combining line coding, FEC, HCM and OCR. In combination with Table 1, it is possible to obtain the data rate for each transmission mode.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| PAM level/ spectral efficiency [bit/s/Hz]  | FEC RS(n,k) | Line code | HCM | Optical Clock Rates/MHz | Data Rate/Mbps |
| 2 / 1 | (256, 248) for payload | 8B10B | (1,1) | 100/2N with N=1/2, 1, …5 | use Table 1 for HCM(1,1) and take into account ii) spectral efficiency for M-PAM i) overhead for HCM instead of 8B10B, see Table 6 |
| (36,24) for header |
| 2 / 1 | 1B1B | (1-15,16) |
| 4 / 2 |
| 8 / 3 |
| 16 / 4 |

**Table 7 Transmission modes using combinations of M-PAM and Line Coding or HCM**

**1.2.4.7 Spatial Precoder for the Payload**

The spatial precoder is a matrix-vector operation ***P****·****x*** operating symbol-wise when using time-domain RS and subcarrier-wise when using frequency-domain RS.

If FT=0 (transport frame), mathematically, the transmitter multiplies the 1xNIRS vector of data symbols ***x***with the NERSxNIRS precoding matrix ***P.*** The master coordinator in the infrastructure network computes the required individual weight factors in the precoding matrix ***P***, splits the data into streams contained in vector ***x*** and passes streams to the used transmitters in a coordinated transmission cluster so that they can be send out in a synchronous manner.

If FT=1 (probe frame), mathematically, the transmitter multiplies the 1x1 scalar stream of data symbols *x* with the NERS x 1 vector ***P*** which contains all ones. In this way all transmitters broadcast the same information. The master coordinator in the infrastructure network passes information to all transmitters so that it is sent out in a synchronous manner.**References**

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**Annex**

1. **Pseudo-noise sequences A**N

The following base sequences are the first from two mother sequences of length N=2k with k=1…11 usually used to form a set of Gold sequences. A ‘1’ is added to keep the sequence balanced.

**A**2 = [-1 1]

**A**4 = [-1 1 -1 1]

**A**8 = [-1 -1 1 -1 1 1 -1 1 ]

**A**16 = [-1 -1 -1 1 -1 1 -1 -1 1 1 -1 1 1 1 -1 1]

**A**32 = [ -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 -1 1 1 1 -1 1]

**A**64 = [ -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 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 1 1 1 1 -1 1 1 1 1 1 -1 1]

**A**128 = [ -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 -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 -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 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 1 -1 1 1 -1 -1 1 -1 1 1 -1 -1 -1 -1 1 -1 -1 -1 1 1 1 1 -1 1]

**A**256 = [ -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 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 -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 -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 -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 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 -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 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 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 1 1 1 -1 1 -1 -1 1 1 1 -1 -1 -1 -1 1 -1 1 1 1 1 -1 1]

**A**512 = [ -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 -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 -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 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 -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 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 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 -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 -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 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 -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 -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 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 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 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 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 -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 -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 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 1 -1 -1 -1 -1 -1 1 -1 -1 -1 -1 1 1 1 1 1 -1 1]

**A**1024 = [-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 -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 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 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 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 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 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 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 -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 -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 -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 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 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 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 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 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 -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 -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 -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 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 -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 -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 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 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 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 -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 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 -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 -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 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 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 -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 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 -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 -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 -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 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 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 -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 -1 1 1 1 1 1 1 1 -1 1 ]

1. **Gray codes for M-PAM**

 **Gray code for 2-PAM**

|  |  |  |
| --- | --- | --- |
| **Decimal** | **Binary** | **Gray** |
| 0 | 0 | 0 |
| 1 | 1 | 1 |

 **Gray code for 4-PAM**

|  |  |  |
| --- | --- | --- |
| **Decimal** | **Binary** | **Gray** |
| 0 | 00 | 00 |
| 1 | 01 | 01 |
| 2 | 10 | 11 |
| 3 | 11 | 10 |

 **Gray code for 8-PAM**

|  |  |  |
| --- | --- | --- |
| **Decimal** | **Binary** | **Gray** |
| 0 | 000 | 0000 |
| 1 | 001 | 0001 |
| 2 | 010 | 0011 |
| 3 | 011 | 0010 |
| 4 | 100 | 0110 |
| 5 | 101 | 0111 |
| 6 | 110 | 0101 |
| 7 | 111 | 0100 |

**Gray code for 16-PAM**

|  |  |  |
| --- | --- | --- |
| **Decimal** | **Binary** | **Gray** |
| 0 | 0000 | 0000 |
| 1 | 0001 | 0001 |
| 2 | 0010 | 0011 |
| 3 | 0011 | 0010 |
| 4 | 0100 | 0110 |
| 5 | 0101 | 0111 |
| 6 | 0110 | 0101 |
| 7 | 0111 | 0100 |
| 8 | 1000 | 1100 |
| 9 | 1001 | 1101 |
| 10 | 1010 | 1111 |
| 11 | 1011 | 1110 |
| 12 | 1100 | 1010 |
| 13 | 1101 | 1011 |
| 14 | 1110 | 1001 |
| 15 | 1111 | 1000 |

**Beacon fields to be considered by MAC layer**

|  |  |  |  |
| --- | --- | --- | --- |
| **Field** | **Octet** | **Bits** | **Description** |
| OWPAN ID | 1 | [7:0] | OWPAN ID |
| SID | 2-3 | [15:0] | Source ID |
| DID | 4-5 | [15:0] | Destination ID |
| OWPAN name | 22-53 | [255:0] | Character-based ID of OWPAN |
| CAP duration after beacon | 13-16 | [31:0] | Duration of CAP in SF, 10 ns resolution |
| BPOS | 11-12 | [15:0] | Beacon slot in each frame, 10 ns resolution |