**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 (PM) PHY enables moderate data rates from 1 Mbit/s to some 100 Mbit/s. The main approach is to achieve high data rates by using a high optical clock rate (OCR) while keeping spectral efficiency low. This approach offers enhanced reach in applications where power efficiency is an issue, e.g. in uplink and in the Internet of Things (IoT). 2-Pulse-Amplitude Modulation (PAM) with 8B10B line coding and variable optical clock rate or M-ary PAM with Hadamard-Coded Modulation (HCM) are used, together with Reed-Solomon (RS) forward error correction (FEC). Controlled by higher layers, the PM PHY includes means to adapt the data rate and reliability of the link to varying channel conditions by i) varying the OCR, ii) varying the modulation alphabet size M for PAM and the number of codes used in HCM and iii) selecting the most appropriate set of transmitters.

The numerology of the PM PHY is defined in Table 1, where only case i) is considered.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Opt. clock rate /MHz** | **Opt. clockcycle/ns** | **Tseq/ns** | **TCP/ns** | **Nseq/optical clock cycles** | **NCP/optical clock cycles** | **MCS for payload** | **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**

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/2n where n = -1…4. The reference clock can also be obtained via Ethernet using the precision time protocol (PTP) defined in IEEE std. 1588v2. Jitter can be further improved by combining PTP with synchronous Ethernet (SynchE) defined in ITU-T rec. G.8262.

* 1. **PPDU format**

Preamble

Channel estimation

SHR

PHY header

HCS

Optional Fields

PHR

PSDU

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 (PSDU).

**1.2 Transmission**

**1.2.1 Synchronization Header (SHR)**

**1.2.1.1 Preamble**

The Preamble enables both, cross- and autocorrelation with an appropriate window size [1-4].

**ETRI proposal:** As a base sequence **A**31, a specific pseudo-noise sequence of length 31 is used, see Annex 1). In the preamble, **A**31 is repeated two times yielding a total sequence length of 62. The total preamble reads [**A**31 **A**31]. The preamble is finally passed through the 2-PAM Modulator.

**HHI proposal:** As a base sequence **A**64, a specific pseudo-noise sequence of length 64 is used, see Annex 1). In the preamble, **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 sequence of the same total length [4]. The total preamble reads [**A**64 **A**64 **A**64 **A**64 **A**64 **A**64] where x=1-x for elements of the sequence. The preamble is finally passed through the 2-PAM Modulator.

**1.2.1.2 Channel estimation**

Channel estimation (CE) is needed for equalization and subsequent detection of header information and data. Although defined in the time domain, the CE sequence allows frequency-domain equalization and hence consists of a base sequence and a cyclic prefix (CP). Measured in time units, the time durations of both, the base sequence Tseq and the cyclic prefix TCP, are maintained, independent of the OCR. By increasing OCR, the number of clock cycles for the sequence and for the CP, i.e. Nseq and NCP, respectively, increase proportionally, see Table 1. As CE sequence, a specific pseudo-noise sequence **A**N given in Appendix 1) is used having length N=2k (k=5…11), depending on the OCR so that N=Nseq (see Table 1). The CE sequence is finally passed through a 2-PAM modulator.

**1.2.2 Physical Layer Header (PHR)**

**1.2.2.1 PHY header**

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 |
| **MCS** | 3-6 | [31:0] | Modulation and Coding Vector for PSDU |
| **RS\_type** | 7 | [7:0] | Type of RS |
| **NRS** | 8 | [7:0] | Number of RS |
| **Time stamp** | 9-12 | [31:0] | Time when frame was sent |
|  |  |  |  |

**Table 2 Fields in the PHY header**

**FT** defines the frame types

FT=0 Probe frame (used as a beacon and for channel estimation)

FT=1 Transport frame (used for data, control and management messages)

FT>1 Reserved

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

**MCS** defines the used modulation and coding schemes. MCS is a number for single-stream transmission. For spatial multiplexing, MCS is a vector where each element contains the MCS per stream controlled by the MAC layer. If FT=0, then single-stream transmission is always used.

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

**Table 3: Descriptor for MCS*.***

**RS\_type** defines the use of time- or frequency-domain reference signals (RS) in the optional field. RS\_type also defines the comb spacing (CS).

|  |  |  |  |
| --- | --- | --- | --- |
| **Field** | **Octet** | **Bits** | **Values** |
| Domain | 7 | [2:0] | 0: time domain1: frequency domain2…7: reserved |
| CS  | 7 | [7:3] | CS =0 : Δ=1…CS=31: : Δ=32 |

**Table 4 Descriptor for RS\_type**

**NRS** is the number of RS in the optional field. The sequence index for the RS to be used is assigned to each transmitter through the PHY SAP.

**Time stamp** is needed to synchronize time between coordinators and devices. It is particularly useful to identify the time when the channel has been measured. It is important to keep channel state information consistent when coming from multiple sources. Time stamp is a number counting time, e.g. in 10 ns units per second. Time per second is obtained from the one-pulse-per-second (1 PPS) signal from GPS or PTP grandmaster. Additional information, can be obtained via higher layers.

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**1.2.2.2 HCS**

The header check sequence (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**

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. MIMO RS can be defined in time- and frequency domain. The use of time- or frequency-domain RS is configured by higher layers. At lower OCR, typically, time-domain RS are appropriate. At higher OCR, frequency-domain RS apply.

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

Time-domain RSs apply at lower optical clock rates and for transmission without FDE. They are also used for single-stream transmission. Time-domain RSs are constructed as follows

* for the ith data stream/transmitter in case of IRS/ERS, respectively, use the ith row of the NxN Hadamard matrix **H**K where N=Nseq according to Table 1. Matrix **H**K is given by



by incrementing k from k=1…K with N=2K. The resulting sequence is scrambled by logical XOR operation with the base sequence **A**N. A cyclic prefix is finally inserted.

All pairs of sequences in **H**K are mutually orthogonal. The XOR operation with **A**N does not change the orthogonality of sequences but improves cross-correlation properties which is beneficial in case of multi-path [5, 6]. Note that the sequence for the first stream/transmitter contains **A**N.

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

Frequency-domain RSs apply for transmissions at higher OCR using FDE. Moreover, they allow orthogonal transmission and detection of RSs for multiple streams or multiple transmitters in the frequency domain.

* Frequency-domain RS are orthogonal in the frequency domain.
* Frequency-domain RSs are a set of NRS OFDM symbols constructed by using the base sequence **A**N where N=Nseq according to Table 1 as follows.
* A specific comb of subcarriers in the frequency domain identifies a stream/transmitter.
* Comb spacing *Δ* is defined by higher layers taking the relation *Δ≤Nseq/NCP* into account.
* The definition of *Δ* is contained in RS\_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 these tines.

* For the first stream/transmitter, the comb starts at the first subcarrier following the DC subcarrier onto which the first element of AN is mapped, while other subcarrier carry the other elements of AN consecutively.
* By using a single FD MIMO RS, up to Δ streams/transmitters can be identified by a cyclic shift of the comb by Nshift=0…Δ-2 of subcarriers.
* The MAC layer shall reserve the shift Nshift = Δ-1 for noise estimation at the receiver.

Any subset of streams/transmitters smaller than Δ-1 can be identified by a single RS. When using more than Δ-1 streams or transmitters, add more RSs. Higher layers shall indicate this by variables Δ and NRS, where index RS means ERS and IRS, accordingly.

In order to keep RSs for multiple subsets of streams/transmitters mutual orthogonal, the mth RS is 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 subset of RSs using the same comb shift.

**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 optional to randomize uncoordinated interference. For error protection, the header can be repeated. Next, 8B10B line encoding applies to the header. Header encoding uses RS(36, 24) code as defined below. According to [12, 13], this particular order of line and channel coding achieves the lowest error rate. After FEC, 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**

Scrambling is defined by the MAC layer and considered optional. If used, scrambling is based on a pseudo-random binary sequence (PRBS) being characteristic for a given data stream.

**1.2.3.3 Line Encoder**

In the header the line encoder 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 is based on 2-PAM. Each input bit is mapped onto one symbol as {0, 1} to {0, 1}, respectively. A constant value of 0.5 is then subtracted to make the output DC free. Setting the modulation amplitude and the bias of the LED is due to the optical frontend.

**1.2.3.6 Spatial Precoder for the Header**

The spatial precoder is the same as for the payload, see 1.2.4.7.

**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 control and management information defined by the MAC layer.



**Figure 3 Transmitter structure for the payload**

Scrambling is optional to randomize uncoordinated interference. 8B10B line coding is applied first. For FEC, the payload uses RS(256, 248) code as defined below. According to [12, 13], a particular order of line and channel coding achieves lowest error rates. After FEC, only the systematic part of the binary output code word (248 bits) is well balanced. For maintaining a constant average light output, 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), 8B10B line coding is not used while M-PAM with M≥2 can be used. A spatial precoder selects finally what set of transmitters will sent out the payload and how.

**1.2.4.2 Scrambler**

Scrambling is defined by the MAC layer and considered optional. If used, scrambling is based on a pseudo-random binary sequence (PRBS) being characteristic for a given data stream.

**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, $\frac{1}{3}$. $\frac{2}{3}$, 1}, respectively. With arbitrary M, symbols map to signal levels as $\{0,\frac{1}{M-1},\frac{2}{M-1}, . . . , 1\}$. Gray mapping tables for M=2, 4, 8 and 16 are found in Appendix 2). A constant value of 0.5 is always subtracted to make the 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. Besides removing the need for line coding, HCM allows the use of M-PAM with variable M, despite the high-pass characteristics of the channel, together with a variable number of codes.



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

 As shown in **Figure 4**, HCM, multiples a vector of N data symbols (where $N$ is a power of two) with a Hadamard matrix, denoted as fast Walsh-Hadamard transform (FWHT). As described in [8], the HCM signal $x = [x\_{0}, x\_{1}, · · · , x\_{N-1}]$ is generated from the data sequence $u = [u\_{0}, u\_{1}, · · · , u\_{N-1}]$ as $x= H\_{N} u + \overbar{H\_{N}} (1-u)$, where $H\_{N}$ is the Hadamard matrix of order $N$ [9], and $\overbar{H\_{N}} $ is the complement of $H\_{N}$. The complement of ***H*** is a binary matrix in which each element *h* of the matrix is replaced by 1-*h*. The components of $u$ are assumed to be modulated using PAM. DC is removed by setting $u\_{0}=0.$

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. For instance, using RS(256,248) with 2-PAM, 8B10B and n=4 (6.25 MHz) yields 4.8 Mbit/s while using RS(256,248) with 16-PAM, m=15 for HCM and n=0 (100 MHz) yields 363 Mbit/s.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| 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…4 | use Table 1 for HCM(1,1) and take into account i) spectral efficiency for M-PAM ii) the appropriate code rate of the FECii) overhead for HCM instead of 8B10B, see Table 6 in Annex 3) |
| (36,24) for header |
| 2 / 1 | 1B1B | (1-15,16) |
| 4 / 2 |
| 8 / 3 |
| 16 / 4 |

**Table 5 Transmission modes using combinations of M-PAM and Line Coding or HCM**

**1.2.4.7 Spatial Precoder for the Payload**

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** (probe frame), the transmitter multiplies the 1x1 scalar stream of header symbols ***x*** with the NERSx1 vector ***P*** which contains all ones. **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.

**If FT=1** (transport frame), 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. **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.

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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**2 = [0 1]

**A**4 = [0 1 0 1]

**A**8 = [0 0 1 0 1 1 0 1]

**A**16 = [0 0 0 1 0 1 0 0 1 1 0 1 1 1 0 1]

**A**32 = [0 0 0 0 1 10 0 1 0 1 1 0 1 1 1 1 0 1 0 1 0 0 0 1 0 0 1 1 1 0 1]

**A**64 = [0 0 0 0 0 1 0 1 0 1 0 0 1 1 0 0 1 0 0 0 1 0 0 1 0 1 1 0 1 1 0 0 0 1 1 1 0 1 0 0 0 0 1 1 0 1 0 1 1 1 0 0 1 1 1 1 0 1 1 1 1 1 0 1]

**A**128 = [ 0 0 0 0 0 0 1 1 1 0 0 0 1 0 0 1 1 1 0 1 0 1 1 0 1 0 0 0 0 0 1 0 1 0 1 0 1 1 1 1 0 1 0 0 1 0 0 0 0 1 1 0 0 0 1 1 0 1 0 1 0 0 1 1 0 0 1 1 1 1 1 0 0 1 0 0 1 0 1 0 0 0 1 0 1 1 1 0 0 1 1 0 1 1 1 0 1 1 1 1 1 1 0 1 1 0 1 1 0 0 1 0 1 1 0 0 0 0 1 0 0 0 1 1 1 1 0 1]

**A**256 = [ 0 0 0 0 0 0 0 1 1 0 1 1 1 1 0 1 0 1 1 0 0 0 0 0 1 0 1 0 1 0 1 0 0 0 1 1 1 1 1 0 0 1 1 1 0 1 0 1 0 0 1 1 0 0 1 1 0 1 0 0 0 0 0 0 1 0 0 0 0 1 1 0 0 1 0 0 0 1 0 0 0 1 1 0 1 0 1 0 1 1 0 1 0 1 1 1 0 1 1 0 1 0 0 1 0 1 1 1 0 0 1 1 0 0 0 1 1 0 0 0 0 1 1 1 0 0 1 0 0 1 1 1 1 0 1 1 1 0 1 0 0 0 1 0 1 0 0 0 0 1 0 0 1 0 0 0 0 0 1 1 1 1 0 0 1 0 1 1 0 0 1 0 1 0 0 1 0 0 1 0 1 0 1 1 1 1 1 0 1 1 0 0 0 1 0 0 1 1 0 1 1 0 1 1 0 0 1 1 1 1 1 1 0 0 0 1 0 1 1 0 1 1 1 0 0 0 1 1 1 0 1 1 1 1 1 1 1 0 1 0 0 1 1 1 0 0 0 0 1 0 1 1 1 1 0 1]

**A**512 = [ 0 0 0 0 0 0 0 0 1 1 1 1 0 0 0 0 1 0 0 0 1 1 1 1 0 1 0 0 1 1 0 0 1 0 0 1 0 0 0 0 1 0 1 1 1 1 0 0 0 1 1 0 0 1 1 1 1 0 1 1 0 1 1 1 0 1 0 1 0 0 0 1 0 1 0 0 0 0 1 1 0 1 1 0 1 0 0 0 1 1 0 0 0 1 1 1 1 1 1 0 0 0 1 0 0 0 1 0 1 1 0 0 0 0 1 0 1 0 1 1 0 1 0 1 1 1 1 1 1 0 1 0 1 0 1 0 1 0 0 0 0 0 1 0 1 0 0 1 0 1 1 1 1 1 0 0 1 0 0 0 1 0 0 1 0 0 1 0 1 0 0 1 1 1 1 1 0 1 0 0 0 1 0 0 0 0 0 1 1 1 0 0 0 0 1 1 0 0 1 0 1 1 0 0 1 0 1 0 0 0 1 1 1 0 0 1 0 1 1 1 0 1 0 0 0 0 0 0 0 1 0 1 1 0 1 0 0 1 1 1 0 1 0 1 1 0 0 1 1 1 0 0 1 1 1 1 1 1 1 0 0 1 1 0 0 1 1 0 1 0 1 0 0 1 1 0 1 1 0 0 0 0 0 0 1 0 0 1 0 1 1 0 1 1 0 1 1 0 0 1 0 0 0 0 0 0 1 1 0 1 0 0 1 0 1 0 1 1 1 1 0 1 0 1 1 1 0 1 1 0 0 0 1 0 0 1 1 0 1 0 0 0 0 1 0 0 1 1 1 1 0 0 1 0 1 0 1 0 1 1 0 0 0 1 1 0 1 1 1 1 0 0 1 1 1 0 1 1 1 1 0 1 1 1 1 1 1 1 1 0 1 1 1 0 1 1 1 0 0 1 1 0 1 1 1 0 0 0 1 0 1 0 1 0 0 1 0 0 1 1 1 0 0 0 1 1 1 0 1 1 0 1 0 1 0 1 1 1 0 0 1 0 0 1 1 0 0 0 0 0 1 1 0 0 0 0 1 1 1 0 1 0 0 1 0 0 0 1 1 0 1 0 1 1 0 1 1 1 1 1 0 1 1 0 0 1 1 0 0 0 1 0 1 1 1 0 0 0 0 0 1 0 0 0 0 1 1 1 1 1 0 1]

**A**1024 = [0 0 0 0 0 0 0 0 0 1 1 1 0 0 0 1 1 1 0 1 1 0 0 0 1 0 0 1 1 0 1 0 1 0 0 0 1 0 0 0 0 1 0 1 0 1 1 1 0 0 0 0 1 0 1 1 0 1 0 1 0 1 1 1 1 1 0 1 0 0 0 0 0 0 0 0 1 0 1 0 1 0 1 0 1 0 0 0 0 1 0 1 1 1 1 0 0 0 1 0 1 1 0 1 1 1 0 0 1 1 0 1 0 0 1 0 1 0 0 1 1 0 0 0 0 1 0 1 0 0 1 1 1 0 0 1 1 0 0 0 0 0 0 1 1 0 1 0 1 0 1 0 1 1 0 0 1 1 0 0 1 1 0 1 0 1 1 0 0 0 0 0 1 0 1 1 0 0 0 1 1 1 1 0 1 1 1 0 0 1 0 0 1 1 0 1 1 1 0 1 0 1 1 0 0 1 0 0 0 0 1 0 0 0 1 0 1 0 1 0 0 0 1 1 0 0 1 1 0 0 0 1 0 0 0 1 0 0 0 1 1 0 0 0 1 0 1 0 1 1 0 0 0 1 0 1 1 1 1 1 0 0 0 0 1 0 0 1 0 0 0 1 1 1 1 0 0 1 1 1 0 1 1 0 1 0 1 1 0 1 0 0 1 1 0 0 1 0 1 1 1 0 1 1 1 0 1 0 0 1 0 1 1 0 1 0 0 0 1 0 1 1 0 0 1 1 1 0 1 0 0 1 1 1 1 1 1 0 1 0 1 1 0 1 1 0 1 0 0 0 0 0 1 0 0 0 0 1 1 1 0 0 1 1 1 0 0 1 0 0 0 1 0 0 1 1 1 1 0 0 0 0 1 1 0 1 1 0 0 0 1 1 0 1 0 0 1 1 1 0 1 1 1 1 0 0 1 0 0 0 0 0 0 0 1 1 0 0 0 1 1 1 0 0 1 0 1 0 1 1 0 1 0 1 1 1 1 0 1 1 1 1 0 1 1 0 1 0 0 1 0 0 0 0 0 1 0 1 0 0 0 1 1 1 0 1 0 0 0 1 1 0 1 1 1 1 0 0 0 0 0 1 0 0 1 0 1 0 1 0 1 1 1 0 1 0 0 0 0 1 0 0 1 1 0 0 0 1 1 0 0 0 0 0 1 1 1 1 1 0 0 0 1 1 0 1 1 0 1 0 1 0 0 1 1 0 1 0 0 0 0 1 1 0 1 0 0 0 1 1 1 1 1 0 1 0 1 0 0 1 0 0 1 1 0 0 1 1 1 1 0 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 0 1 0 0 0 0 0 0 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 0 1 1 0 1 0 1 1 1 0 0 1 0 1 1 1 1 1 1 0 0 1 1 0 1 1 0 1 1 1 0 1 1 1 1 1 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 1 1 0 0 1 0 1 0 1 0 0 1 1 1 1 0 1 0 0 0 1 0 0 1 0 1 1 1 0 0 1 1 1 1 0 1 1 0 0 0 0 0 0 0 1 0 0 0 1 1 1 0 0 0 0 1 1 1 1 1 1 0 0 0 1 0 0 1 0 0 1 1 1 0 1 0 1 1 1 0 1 1 0 0 1 1 0 1 1 1 1 1 0 0 1 0 1 1 0 1 1 0 0 0 0 1 0 0 0 0 0 1 1 1 0 1 0 1 0 1 0 0 1 0 1 1 1 1 0 1 0 1 1 1 1 1 1 1 0 1 0 0 1 0 0 1 0 0 0 0 1 1 0 0 0 0 1 1 1 0 1 1 1 0 0 0 0 0 0 1 0 0 1 1 1 0 0 0 1 0 1 0 0 1 0 1 0 1 1 1 1 0 0 1 1 0 0 1 0 0 1 1 1 1 1 0 0 1 1 1 1 1 1 1 1 0 0 1 0 0 1 0 0 1 0 1 0 0 0 1 0 1 0 0 0 0 1 1 1 1 0 1 0 1 0 1 1 0 1 1 1 1 0 1 0 0 1 1 0 1 1 0 0 1 1 1 1 1 0 1 1 1 0 1 1 0 1 1 1 1 1 1 0 1 1 1 1 1 1 1 1 1 0 1 1 0 1 1 0 1 1 0 0 1 0 1 1 0 0 1 0 1 0 0 0 0 0 1 1 0 0 1 1 1 0 0 0 0 0 1 1 0 1 1 1 0 0 0 1 0 0 0 0 0 0 1 1 1 1 0 0 0 1 1 1 1 1 1 1 0 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 |

1. **Overhead for HCM**

Table 6 lists overheads for different values of $N$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,** $N)$ | **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** $N$