**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. for uplink and Internet of Things (IoT). Binary 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 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 is defined in Table 1. Table 1 contains only case i).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **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 200 MHz available from low-cost off-the-shelf crystal oscillators by dividing e.g. the 200 MHz clock as 200 MHz/2n where n=0, 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 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].

When using 8B10B, the base sequence **A**32, a specific pseudo-noise sequence of length 32 is used, see Annex 1). **A**32 is repeated two times yielding a total sequence length of 64. The total preamble reads [**A**32 **A**32]. The preamble is finally passed through the 2-PAM Modulator.

When using HCM, the base sequence **A**N, a specific pseudo-noise sequence of length N is used, see Annex 1). **A**N is repeated six times yielding a total sequence length of 6\*N. Each base sequence is multiplied with positive or negative sign as given below which is known to create a sharper peak after autocorrelation, compared to a double sequence of the same total length [4]. The total preamble reads [**A**N **A**N **A**N **A**N **A**N **A**N] where x=1-x for elements of the sequence. The preamble is finally passed through the 2-PAM Modulator.

|  |  |  |  |
| --- | --- | --- | --- |
| **Payload encoding** | **N** | **Preamble length** | **Header repetitions** |
| 8B10B | 32 | 64  | 1 |
| HCM(1,4) | 16 | 96 | 4 |
| HCM(1,8) | 32 | 192 | 8 |
| HCM(1,16) | 64 | 394 | 16 |

**Table 2 Parametrization of PM PHY preamble and header (see 15-18-0190/r0)**

**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 variable 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 3.

|  |  |  |  |
| --- | --- | --- | --- |
| **Field** | **Octet** | **Bits** | **Description** |
| **Frame Type** | 0 | [7:0] | [0] FT[1] High reliability MAC header[7:2] reserved |
| **PSDU\_length** | 1-2 | [15:0] | Length of PSDU in optical clock cycles |
| **MCS** | 3-8 | [31:0] | Modulation and Coding vector for PSDU |
| **Adaptive transmission** | 9 | [7:0] | [0] Adaptive enabled: : 0=off, 1=on[1] CQI feedback enabled[7:2] reserved |
| **MIMO** | 11-12 | [15:0] | 0: MIMO enabled, 0=off, 1=on1: **RS\_type**[7:2] **NRS** (Number of RS)[12:8] **CS**[15:13] reserved |
| **Relaying**  | 13 | [7:0] | [0] Relaying enabled: 0=off, 1=on [1] Relay mode: 0=AF, 1=DF[[1]](#footnote-1)[2] Relay duplex mode: 0=TD, 1=FD[[2]](#footnote-2)[7:3] reserved |

**Table 3 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)

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 of streams send to different devices or to the same device having multiple receive branches, MCS is a vector where each element contains the MCS per stream being controlled by the MAC. If FT=0, then single-stream transmission is always used. The code index vector IHCM is a binary vector of 16 bits indicating by a “1” at ith position that the ith HCM code is being used. Any combination of HCM codes can be assigned in this way.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Field** | **Octet** | **Bits** |  | **Values** |
| Stream 1 | 3-5 | [0] | reserved | reserved |
| [3:1] | Modulation | 0:2-PAM…3:16-PAM>3: reserved |
| [7:4] | NHCM | 0: 8B10B is used1: NHCM=12: NHCM=2…15: NHCM=15 |
| [23:8] | code index vector IHCM | Bit0: always “0” Bit1: 2nd code usedBit3: 3rd code used…Bit15: 16th code used  |
| Stream 2-4 | 6-8 | [31:8] | … | … |

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

**Adaptive transmission** allows the PM PHY to be operated in variable channel conditions by selecting an appropriate MCS according to the channel. The device can be configured to provide Channel Quality Indicator (CQI) feedback[[3]](#footnote-3).

When using MIMO, **RS\_type** defines the use of time- or frequency-domain reference signals (RS) in the optional field. **NRS** is the number of RS in the optional field. The sequence index for the specific RS to be used is assigned to each transmitter through the PHY SAP.

|  |  |  |  |
| --- | --- | --- | --- |
| **Field** | **Octet** | **Bits** | **Values** |
| **RS\_type** | 9-10 | [1] | 0: time domain1: frequency domain |
| **CS**  | 9-10 | [12:8] | CS=0 : Δ=1…CS=31: : Δ=32 |

**Table 5 Descriptors for MIMO**

**Relaying mode** specifies the mode of relaying operation (amplify-and-forward, decode-and forward). **Relay duplex mode** specifies the duplex mode for relaying (time- or full duplex).

**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 configurable via the MAC SAP. 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 (TD) RSs are orthogonal in the time domain and constructed as follows. For the ith data stream/transmitter, respectively, TD RS use the *i*th row of the NxN Hadamard matrix **H**K where N=Nseq=2K according to Table 1. The value of *i* is used to identify the specific transmitter and defined by the MAC via the PHY SAP. Matrix **H**K is obtained iteratively by incrementing k from k=1…K as

.

The resulting sequence is scrambled symbol-wise by logical XOR operation with the base sequence **A**N after subtracting a constant value of 0.5 from **A**N. A cyclic prefix is finally inserted, with length NCP=Nseq/32.[[4]](#footnote-4)

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

Frequency-domain (FD) RSs allow orthogonal detection of multiple data streams or signals from multiple transmitters and are orthogonal in the frequency domain. A specific comb of subcarriers identifies a particular stream or transmitter.

Construction of FD RS starts from the base sequence **A**L in Annex 1) where L=Nseq/(2\*Δ) according to Table 1 and comb spacing Δis a power of 2. The value of Δ is defined by the MAC via the PHY SAP taking the fundamental relation Δ*≤Nseq/(2\*NCP*) into account yielding. Following values of L are used for a given OCR.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **OCR/MHz** | **6.25** | **12.5** | **25** | **50** | **100** | **200** |
| **Nseq** | 32 | 64 | 128 | 256 | 512 | 1024 |
| **L(Δ=1)** | 16 | 32 | 64 | 128 | 256 | 512 |
| **L(Δ=2)** | 8 | 16 | 32 | 64 | 128 | 256 |
| **L(Δ=4)** | 4 | 8 | 16 | 32 | 64 | 128 |
| **L(Δ=8)** | 2 | 4 | 8 | 16 | 32 | 64 |
| **L(Δ=16)** | 1 | 2 | 4 | 8 | 16 | 32 |

**Table 6 Base sequence length L for FD RS depending on the OCR and the comb shift Δ.**

1. A constant bias 0.5 is subtracted from **A**L.
2. AL is up-sampled by factor Δ.
3. A cyclic shift by S samples applies to sequence vector **Y** yielding sequence vector **Z**. The sequence **Z** has length of Lz=L\**Δ*. The value of S identifies the specific stream or transmitter and is defined by the MAC via the PHY SAP. The MAC layer shall reserve the shift S=Δ-1 for noise estimation at the receiver.
4. Sequence **F** is formed as follows **F**=[0 **Z**(1:LZ-1) 0 **Z**(LZ-1:-1:1)]. This will implement Hermitian symmetry in the next step. Note that the first LZ-1 samples from sequence **Z** are used twice, first in the original and then in the reversed order.
5. Finally, the sequence **F** is passed through an inverse fast Fourier transform (IFFT) which always yields a real-valued RS being specific for a given stream or transmitter.

By using a single RS, up to Δ-1 streams or transmitters can be identified. The MAC layer will add more RSs via the PHY SAP for more streams or transmitters as indicated by NRS being a power of 2. In this way, up to NRS\*(Δ-1) streams can be identified. Decompose the identifier of the ith stream or transmitter as i=a\*(Δ-1)+b where b<Δ-1. The comb shift is then S=b and the original RS is multiplied RS by RS with the entries in the *a*th row of the MxM Hadamard matrix **H**K where M=2K. **H**K is obtained by incrementing k from k=1…K

.

**1.2.3. Header encoding and modulation**

**1.2.3.1 General**

The transmitter structure in Figure 2 applies to the header. Scrambling is optional to randomize uncoordinated interference. For improved error protection, the header can be repeated. 8B10B line encoding applies to the header. Header encoding uses RS(36, 24) as defined below. According to [12, 13], a particular order of line and channel coding shown in Figure 2 achieves 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) passes 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 can be defined by the MAC layer through the PHY SAP. 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 applies 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 shown in Figure 3 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) passes 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 can be defined by the MAC layer through the PHY SAP. 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 M-PAM. DC is removed by setting $u\_{0}=0.$

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| 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) | 200/2n with n=0, 1, …, 5 | 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**

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.

**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**1= [1]

**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** $N$

1. AF = amplify-and-forward, DF = decode-and-forward [↑](#footnote-ref-1)
2. TD = time division duplex, FD = full duplex [↑](#footnote-ref-2)
3. For PM PHY, CQI feedback is defined as a 6 bit number measuring the value of CQI=SINR+10 dB, i.e. CQI=0: SINR <-10 dB; CQI=1: SINR=-9 dB … CQI=63: SINR=+53 dB after in front of the FEC decoder. CQI feedback is computed at the receiver and sent by the MAC layer in a control message obver the reverse link to the transmitter side. [↑](#footnote-ref-3)
4. All 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 or transmitter just contains **A**N. [↑](#footnote-ref-4)