**IEEE P802.15**

**Wireless Personal Area Networks**

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| Abstract | [This document contains an updated description of the high bandwidth PHY for inclusion into D0.] | |
| Purpose | [This document shall be integrated into the draft D0.] | |
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# PHY Layer Operating mode(s)

**Dear Proposer: please fill in this section with your PHY operating mode(s). You may modify this table as you see fit.**

See table 73, 74 or 75 from IEEE802.15.7-2011 for an example table.

Table 1‑1 – Overview of PHY operating modes

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **PHY Operating Modes[[1]](#footnote-1)** | | | | |
| **modulation** | | | DC-biased DMT | |
| **subcarrier spacing** | | | 195.3125 kHz | |
| **cyclic prefix (CP)** | | | 160, 320 ns | |
| **symbol duration (w/o CP)** | | | 5.12 µs | |
| **FEC** | | | Low-density parity-check code (LDPC) | |
| **information block size** | | | 120, 540 bytes | |
| **code rates** | | | 1/2, 2/3, 5/6, 16/18, 20/21 | |
| **repetitions** | | | 1, 2, 3, 4, 6, 8 | |
| **Bandwidth** | **Optical Clock Rate (Factor)** | **Used Carriers**  **(IFFT size using DMT)** | | **Min. to Max. Data Rate[[2]](#footnote-2)** |
| 10 MHz | 25 MS/s (1/8) | 45 (128) | | 1.5 to 103 Mb/s |
| 25 MHz | 50 MS/s (1/4) | 107 (256) | | 3 to 257 Mb/s |
| 50 MHz | 100 MS/s /1/2) | 215 (512) | | 7 to 512 Mb/s |
| 100 MHz | 200 MS/s (1/1) | 450 (1.024) | | 14 to 1.028 Mb/s |
| 200 MHz | 400 MS/s (2/1) | 950 (2.048) | | 35 to 2.056 Mb/s |
| 500 MHz | 1 GS/s (5/1) | 2375 (2x 2.048) | | 87 to 5.140 Mb/s |
| 1 GHz | 2 GS/s (10/1) | 4750 (3x 2.048) | | 145 to 10.281 Mb/s |

# PHY specifications: High-bandwidth PHY

**Dear Proposer: please fill in this section with your PHY specifications**

See IEEE802.15.7-2011 sections 10, 11 or 12 for current specifications.

**< Enter PHY specifications here >**

## Introduction

The high-bandwidth PHY extends the capabilities and improves the transmission performance in order to address the specific requirements of new use cases in scenarios B1-B4 mentioned in the Technical Considerations Document (TCD) for 802.15.7r1 [8], such as optical wireless access in indoor/home/office, industrial wireless (with specific requirements for robustness, low latency and secure data transmission), communications between vehicles and vehicle-to-the-roadside-infrastructure communications, and as a wireless backhaul technology.

### Scope

The high-bandwidth PHY supports fixed wireless links and multiple mobile user links via an OWC infrastructure, which consists of one or more optical wireless access points. The PHY is wavelength-agnostic and extends the optical wavelength range beyond the scope of 802.15.7 standard for visible light communication (VLC) also below and above the wavelengths of 380 nm and 780 nm, respectively hereby including the invisible light. A wide range of data rates (i.e., 1 Mb/s to 10 Gb/s) are supported, targeting an efficient use of the optical bandwidth also under time-variant channel conditions.

The high-bandwidth PHY introduces modern wireless transmission technologies, such as orthogonal frequency-division multiplexing (OFDM), adaptive transmission, multiple-input multiple-output (MIMO) and coordinated wireless networking of multiple access points (APs) to provide mobility for mobile user devices (UDs) in an OWC network infrastructure. In addition, specific requirements for enhanced robustness and lower latency are addressed to support e.g. industrial wireless, vehicular and backhaul scenarios (B2, B3, B4).

For coordinated networking, unified interfaces are introduced for the user plane and an open interface to the control plane, which can be used at the network layer to manage the interference between parallel optical wireless links and to support user mobility. These interfaces enable also the coexistence of OWC with radio based wireless links.

### Network topologies

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| Figure 3‑1 – New network topologies coordinated wireless (COW) and wireless relaying (WREL) |

The high-bandwidth PHY supports three new topologies, i.e. coordinated wireless (COW), heterogeneous network (HET) and relaying (WREL), as shown in Figure 3‑1 and Figure 3‑2 in addition to the point-to-point (P2P), broadcast (BC) and star (S) topologies already described in 802.15.7-2011. In COW topology, mobility among multiple access points (APs), i.e. handover and interference coordination is supported. In the HET topology, optical wireless and radio frequency (RF) transmissions can be combined. In the WREL topology, the high-bandwidth PHY supports data transport including intermediate relays.

The high-bandwidth PHY defines all methods at the PHY layer for operating the link in P2P, S, COW, HET and WREL topologies. It is defined by higher layers (above the PHY) in which topology the link is operated. The PHY supports the respective data transport and control signaling needed in the respective topology.

#### Point-to-point

In the P2P topology, two UDs can connect to each other and establish a wireless link. The P2P link is defined such that it may serve as a wireless replacement of an Ethernet cable in any computer or telecommunication networks. Besides specifying the fundamental PHY architecture for all topologies, the MAC layer is assumed to support an automatic link setup and a feedback path for closed-loop frequency-selective link adaptation.

#### Star

In the S topology, one UD acts as AP serving multiple other UDs in parallel. The AP aggregates the traffic from multiple UDs and coordinates their wireless transmission. The S topology requires additional functionalities. The PHY supports time-division multiple access (TDMA) and frequency-division multiple access (FDMA). Feedback from UDs is transmitted in an orthogonal manner via the PHY, i.e., contention-free. An additional control channel is broadcast via the PHY to all UDs containing information about granted transmission resources for uplink and downlink directions.

#### Coordinated wireless network

In the COW topology, multiple UDs are served by multiple APs, which are in turn coordinated by a network controller (NC). The NC is a device that has a fixed network link to the APs. The NC reroutes the traffic paths between NC and APs in case of handover and controls the transmission of all APs and UDs to manage interference. APs are time-synchronized, what can be achieved e.g. by the IEEE 1588 precision time protocol (PTP). The NC aggregates the wireless traffic of UDs and APs. However, its functionality is not part of 802.15.7r1. Only the specific data transport and control signaling needed in the COW topology are defined. Based on cell-specific reference signal, UDs and APs estimate the interference channel in down- and uplink directions, respectively. The corresponding metrics reports are conveyed in the downlink over the wireless uplink and via the APs to the NC and ii) in the uplink via the APs to the NC where it is used for interference coordination and handover.

#### Heterogeneous network

In the HET topology, there are 3 types of devices based on its capability of support OWC and RF. Table 4‑1 shows the 3 different types of devices.

Table 4‑1 Device types

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Device type | RF down link | RF uplink | OWC downlink | OWC uplink |
| Type 1 |  |  | √ | √ |
| Type 2 | √ | √ | √ |  |
| Type 3 | √ | √ | √ | √ |

Type 1 devices only have OWC transceivers, therefore only VLC links are available. Type 2 and type 3 devices have both OWC transceivers and RF transceivers and both OWC links and RF links are available. Therefore a heterogeneous network comprised of both OWC links and RF links can be formed as sown in Figure 3‑2. Coordinators, which are LED lamps, are located at the room ceiling. Each coordinator is connected to the global controller through the backhaul link. The backhaul link is probably based on wired link, e.g., power line link. The global controller distributes downlink traffic to different coordinators and manages handover and interference coordination between different VPANs. Each coordinator provides OWC access to one or multiple devices. Type 2 and type 3 devices are connected to the global controller through RF links. The RF access point (AP) can be co-located at the global controller.

In the downlink direction, joint transmission through both OWC link and RF link and handover between OWC link and RF link are possible for both type 2 and type 3 devices. For type 2 devices, uplink traffic shall be transmitted through RF link and OWC command frames and ACK frames that need to be transmitted to the coordinator shall be first transmitted to the global controller through RF link and then forwarded to the coordinator through the backhaul link.

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| Figure 3‑2 Heterogeneous network comprising of both RF links and VLC links |

A heterogeneous network can have devices of all the three types. The global controller and coordinators shall distribute traffic and transmission opportunities to devices based on their capabilities of support RF and OWC.

#### Wireless relaying

In the REL topology, an intermediate relay device (RD) is enabled to assist a transmission via a direct optical wireless link which may be shaded or blocked or in a bad signal condition. Both, classical relaying as well as cooperative relaying are supported. In this topology, it is assumed that each RD has multiple capabilities including duplexing and relay modes. For duplexing mode, the RF supports either full duplex (FD), where the RF receives and transmits data simultaneously, while in half duplex (HD), the RF receives the data in one time slots and retransmits the data in another time slot. For the relaying mode, the RD supports two modes; amplify-and-forward (AF), and decode-and-forward (DF) modes. In AF mode, the RD receives the data from the AP, which are then retransmitted after amplification to mitigate the channel degradation occurred during transmission from AP to RD. In DF mode, the data received by the RD is fully decoded and then retransmitted from the RD to the UD. In case the link between the AP and UD is disconnected, the AP will initiate a RD search request. Each The AP broadcasts a search RD request frame. Each RD replies back on the control channel with its own capabilities including duplexing and relaying modes. The AP selects the RD that provides the best performance according to a specific criterion. The AP initiates a relay setup link procedure between the AP, selected REL and the UD. A connection remains active until the direct link between the AP and UD is reinitiated and the AP requires a termination of the link between the AP and REL.

### Essential Features

#### Use cases

The high-bandwidth PHY supports all use cases B1-B4 and all light sources described in [8].

#### Transfer mode

The high-bandwidth PHY supports bidirectional, continuous and packet-based OWC.

#### Scalable data rates

The high-bandwidth PHY supports variable data rates from 1 Mbit/s to 10 Gbit/s by means of a scalable design. In all PHY modes, subcarrier spacing and cyclic prefix (CP) are the same. Used bandwidth is scalable by adapting number of used subcarriers. Interoperability among all PHY modes is enabled, i.e. a transceiver with a smaller bandwidth can synchronize with respect to, and exchange control information and data with, another transceiver having a higher bandwidth and vice versa. Bandwidth adaptation is supported to operate the link at the lowest bandwidth during link setup, and uses subcarriers at low frequencies only to transmit control information, before switching eventually to a higher bandwidth mode.

#### Waveform

An adaptive, real-valued OFDM waveform denoted as DC-biased discrete multi-tone (DMT) is used. It can be extended by an optional preprocessing in order to improve energy efficiency. Moreover, adaptive bit- and power loading is supported using variable modulation formats on each subcarrier or on groups of subcarriers, depending on the channel-, interference- and noise-characteristics of the optical wireless link.

#### Efficient use of the optical bandwidth

The high-bandwidth PHY supports the efficient use of the optical bandwidth by means of a highly scalable PHY layer design, together with closed-loop adaptive transmission and the efficient support of MIMO, cooperative transmission and relaying. This combination allows robustness in the multi-path propagation channel, in case of mobility and in interference scenarios. Moreover, PHY is defined so that one-way latencies of 1 ms are achievable.

#### Dimming support, coexistence

The high-bandwidth PHY allows dimming for use cases B1, B2 and B3 in the TCD [8]. Due to adaptive transmission, coexistence is supported with ambient light and other light sources.

#### Metrics reporting

The high-bandwidth PHY provides metrics to be reported for efficient operation of higher layer protocols. Depending on the topology, metrics to be reported comprise signal strength of strongest APs and UDs, frequency-selective signal-to-interference-and-noise ratio (SINR) and channel state information (CSI) for strongest APs and UDs. Short time intervals between metric reports and control messages are enabled targeting fast adaptation to the time-varying wireless channel, low latency and minimal overhead.

#### Advanced wireless networking, high availability

The high-bandwidth PHY allows robust wireless transmission and thereby high availability for all channel conditions. Advanced wireless networking is supported in S, COW, HET and WREL topologies. The link is available in both, line-of-sight (LOS) and non-LOS (NLOS) scenarios, at low signal-to-noise-and-interference ratio (SNIR) and in interference-limited conditions.

## Adaptive OFDM

The idea of the adaptive OFDM physical layer is shown in Figure 2‑2. At the transmitter (Tx), the input data are transported via orthogonal subcarriers. Each data symbol carrying one or more bits is mapped onto a constellation point, according to a variable modulation format for each subcarrier. A Hermetian symmetry operation is then performed to create a real-valued waveform. An OFDM symbol is generated by feeding symbols in the frequency domain into the inverse fast Fourier transform (IFFT) followed by the insertion of a cyclic prefix (CP). The output of the OFDM signal is then clipped in the digital domain and passed through the digital-to-analog converter (DAC) and low-pass filter (LPF). A bias is normally added to ensure a unipolar all positive signal before it is used for intensity modulation of the optical source (i.e., light emitting diode (LED) or a laser diode (LD)).

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| Figure 3‑3 - Overview of the standalone link (one link direction). |

Following conversion from optical to electrical signal and signal detection, the inverse operations are performed at the receiver (Rx), where a frequency-domain equalizer (FDE) is used to reconstruct the received constellation points on each sub-carrier, after passing them through the OWC channel. The desired mapping of information bits onto the sub-carriers is sent by the receiver to the transmitter over the reverse link. In the example shown in Figure 2‑2, the metrics reporting is carrying a so-called noise-enhancement vector. A power- and bit-loading algorithm determines the power and modulation formats for the data transport on each used subcarrier. The loading algorithm typically maximizes the throughput assuming a fixed power budget so that a predefined bit error rate (BER) is achieved before forward error correction (FEC).

### PHY based on G.hn in coax mode

As the above transmission concept is already realized for other media in home environments, such as twisted pair, coax and transmission over plastic optical fibers, the following specifications take references to the ITU-T recommendation for home networking G.hn that has been recently developed for all these media. The requirements of the TCD can be met by

1. Starting from G.hn PHY baseband coax modes for 50, 100 and 200 MHz bandwidth
2. adding further modes for scalability towards lower and higher bandwidths
3. adding new features for the coordinated wireless (COW) topology
4. adding new features for the wireless relaying (WREL) topology

Starting from the G.hn recommendation is efficient because optical wireless is an emerging technology expecting fast market growth. The home networking community has developed G.hn for several fixed networking media and is adopting OWC as a next medium to support as an further evolution of G.hn. By aligning the G.hn evolution with the high-bandwidth mode in 802.15.7r1, a powerful new specification is obtained that fulfills the requirements in the TCD by evolving an existing technology rather defining a new one.

In the following, an implementable overview of the necessary features taken over from 2015 release of G.hn is given it is demonstrated how the existing G.hn PHY can be further developed in order to enable the new COW and WREL modes over the optical wireless link.

### Adaptive OFDM Waveform

The PHY uses the adaptive OFDM waveform in both link directions with following extensions:

1. The waveform is always non-negative and real-valued.
2. A bias is added and clipping (if needed) is implemented in the digital domain.
3. Optional single-carrier or unipolar modulation to improve power efficiency and support dimming.

OFDM signal generation is shown in Figure 2‑3. A block of 2*N* data symbols is transmitted. An optional pre-coding is used for the generation of singlecarrier or unipolar modulation schemes based on OFDM to improve power efficiency and support dimming. The signal is then passed through a carrier mapping unit, used for precoding and Hermitian symmetry. Next, the IFFT is performed, the CP is added and controlled clipping is performed in the digital domain.

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| \\hhi.de\abteilung\PN\Groups\Metro, Access  and In-house Systems\Projekte\IEEE 802.15.7r1\Proposals\Bilder\PNG\OFDM Signal Generation.png  Figure 3‑4 - OFDM signal generation |

#### Carrier mapping

Carrier mapping is performed as illustrated in Figure 2‑4. Note that the subcarrier x0 may be used to add a constant bias signal to the output signal. In order to create a real-valued waveform, only half of the subcarriers are used, while conjugate symmetry is enforced as

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where the star indicates complex conjugation. The resulting discrete multi-tone (DMT) signal is real-valued, even if symbols *xi* are complex.

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| \\hhi.de\abteilung\PN\Groups\Metro, Access  and In-house Systems\Projekte\IEEE 802.15.7r1\Proposals\Bilder\PNG\carrier mapping for SA link.png  Figure 3‑5 - Carrier mapping for standalone link |

#### IFFT

The time-domain signal *X(k)* is given by

where *i* denotes the sample index, *xi* the complex-valued baseband signals in the frequency domain and *2N* the block size of the IFFT.

#### Cyclic prefix

At the output of the IFFT, in the serial block of 2N samples, the last CP samples are copied as a sub-block being repeated and appended at the beginning of the block of samples, see . By adding the CP at the transmitter, and removing it at the receiver, the multipath channel matrix can be transformed from Toeplitz-shape into a circulant shape, which allows the use of IFFT at the transmitter and FFT at the receiver to obtain a diagonal channel in the frequency domain, so that a simple single-tap frequency-domain equalizer (FDE) can be used.

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| \\hhi.de\abteilung\PN\Groups\Metro, Access  and In-house Systems\Projekte\IEEE 802.15.7r1\Proposals\Bilder\PNG\CP insertion.png  Figure 3‑6 - Cyclic prefix insertion |

### Single-carrier modulation (optional)

Optional pre-coding before the OFDM modulator can be used to reduce the probability of clipping and enhance power efficiency while sacrificing no or minor spectral efficiency [1, 2].

For single-carrier (SC) transmission, “outer” pre-coding, together with an “inner” OFDM transmitter is used to emulate SC transmission inside the OFDM concept. The novel schemes require little more advanced signal processing, and the same minor increase of sophistication can be expected at the receiver, i.e. decoding is straightforward. The schemes are shown in principle in Figure 2‑6. Details can be found in [1, 2].

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| Figure 3‑7 Different precoding schemes can be used to improve the power efficiency of the OFDM transmitter. Top: Pure DFT precoding uses a roll-off factor =0. Center: A root-raised-cosine filter can be added in the frequency domain, to realize >0. Bottom: A Gaussian filter can used in the same way and a minimum-shift keying (MSK) modulation can be added in the time domain. In this way, the classical GMSK waveform can be realized inside an OFDM system. |

#### DFT-pre-coded OFDM

The simplest SC transmitter is shown in Figure 2‑6 row A. First, the symbol sequence is passed through the N-DFT and then mapped directly onto the desired frequency sub-band after using a cyclic shift (CS) so that the DC signal is in the center[[3]](#footnote-3). Finally, the precoded sequence is passed through the M-IDFT and the cyclic prefix (CP) is added.

As shown in [2], this procedure yields a SC signal having a roll-off factor =0. The rectangular filtering causes “ringing” in the time domain which increases the peak-to-average power ratio (PAPR). As this is a special case of the RRC-filtered SC transmission, details are described in the next subsection.

#### RRC-filtered single-carrier modulation

In the middle row in Figure 2‑6, an additional root-raised-cosine filter is introduced in the frequency domain where ≥0. In order to realize filtering in the frequency domain, oversampling is emulated by repeating the DFT output block in the frequency domain. Afterwards, the root-raised cosine (RRC) filter is applied in the frequency domain. The sequence is then mapped directly onto the desired frequency sub-band using a cyclic shift (CS) so that the DC signal is in the center. In the following, these steps are described in detail.

A data sequence a(n) of length M is used where n = 1, 2, …, M. The sequence is up-sampled by factor *F* as follows

with , where *k =* 1, 2*, …, F∙M* and *2N* is the number of samples in the final waveform w/o the CP. The notation is used here to indicate that *z* is rounded to the nearest integer less than or equal to *z*.[[4]](#footnote-4) Note that F-times up-sampling followed by *M*-DFT is equivalent to *M*-DFT and subsequent spectral repetition, provided that the ratio is an integer. The proof is given in [2]. Accordingly, up-sampling and *2N*-DFT can be replaced by *M*-DFT and repeating the output signal in the frequency domain.

Next step is a flexible frequency-domain filter. It is implemented so that bandwidth can be easily changed as a function of the block size *M*. Therefore, a vector is defined with running index s = [-M, …, M] the bell-shape part of the filter is computed as

where l = 1, 2, …2M+1. The filter is transparent in the range

There are two regions where the filter attenuates totally. They are given by

G*l* is now set as G***a*** = 1, G***b*** = 0 and G***c*** = 0 in the respective regions indicated by vectors ***a***, ***b*** and ***c***. Note that up-conversion is equivalent to performing sequentially 2N-DFT of the time-domain sequence, a cyclic shift by *Ncenter* and 2N-IDFT of the shifted signal, as shown in [2].

In row B. in Figure 2‑6, the synthesis of filtered QAM is summarized in the frequency domain. First the data symbol sequence is passed through the M-DFT and the output is repeated in the frequency domain. Next, the signal is filtered in the frequency domain and the cyclic shift is applied to up-convert the signal to the desired center sub-carrier *Ncenter*. Finally, the signal is passed through the *2N*-IDFT and the cyclic prefix is added [2].

Note that in the SC transmitter, carrier mapping has been modified compared to LTE. In this way, waveforms become comparable to time-domain single-carrier signal, see [2]. The new mapping is sketched in Figure 2‑7.

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| Figure 3‑8 Generation of filtered single-carrier signals. |

The direct current (DC) sub-carrier of the M-DFT output vector (having index 1) is first mapped onto the DC sub-carrier of the 2N-IDFT. The two blocks

and

are then mapped onto the first and last sub-carriers, see Fig. 2. Periodic replica are added in the frequency domain to emulate up-sampling. Finally, the frequency-domain filter is applied and the cyclic shift is used to modulate the signal onto the center subcarrier.

#### Gaussian minimum shift keying

GMSK is known for zero PAPR in radio links. Although this goal is not reached in OWC links, due to the real-valued waveform, GMSK offers ultra- robust signaling in case of very low SINR. First, the classical time-domain GMSK single-carrier transmitter is reviewed. The serial data symbol sequence *a*(n) is up-sampled as in subsection 2.2.2.5.2 yielding *b*(k). After applying a Gaussian filter in the time domain, the filtered signal c(k) is obtained. The classical Gaussian filter is approximated in the time domain using a finite impulse response (FIR) with some memory. Next, c(k) is passed into a minimum shift keying (MSK) modulator where it is first accumulated yielding the phase

and then inserted into the complex amplitude

Note that in-phase signal I and the quadrature signal Q in are fed by the same phase but at a shift of 90° yielding single side band (SSB) modulation when up-converting the sequence to the desired center frequency. This is often performed using an analog IQ modulator. The same SSB up-conversion can be reached by means of digital signal processing. Therefore, the complex-valued GMSK baseband signal is multiplied sample-by-sample with a digitally synthesized complex-valued oscillation due to single OFDM sub-carrier, being the center frequency of the desired GMSK-modulated signal. Finally, a window of length M is applied in the time domain.

The equivalent processing for GMSK using OFDM is summarized on row C. in Figure 2‑6. As before, the data sequence *a*(n) is fed into the M-DFT and up-sampling is emulated by repeating the output signal in the frequency domain. Next, a Gaussian filter is applied in the frequency domain. A vector is created with running index s = [-R, …, R] where R≤M, the filter is computed as

where

where *n* = 1*,* 2*, ...,* 2*R* +1 and *BT* is the bandwidth-time product. BT=0.3 is recommended. GMSK is a non-linear SSB phase modulation. Thus, the two functions of accumulating the signal and generating the in-phase and quadrature signals are better realized in the time domain. The main idea is to insert the GMSK modulator after frequency-domain filtering, but in the time domain. Using *M*-IDFT of the filtered data sequence, *c*(*k*) is obtained. Next, *c*(*k*) is normalized to unit peak amplitude and feed it into the time-domain MSK modulator described above. Then up-conversion is applied. It can be equivalently implemented as shown in row *C* in Figure 2‑6 or in the time-domain as described above. Finally, the CP is added.

GMSK causes adjacent channel interference since SSB phase modulation is a non-linear process. Even if the GMSK modulator input is confined in the frequency domain, four-wave mixing between in-band sub-carriers creates out-of-band interference. Such interference can be cut using an optional post-modulation filter in the frequency domain attenuating totally outside the range s=[−R, ...,R] and correct the power, accordingly.

#### From complex- to real-valued single-carrier transmission

The above waveforms yield complex-valued sequences. Same as in the adaptive OFDM approach, the complex-valued waveform covers only the first N subcarriers and then Hermetian symmetry is needed to generate a real-valued waveform. Conjugate symmetry is obtained as

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The resulting discrete multi-tone (DMT) signal is real-valued, even if symbols *xn* are complex.

1. V. Jungnickel, T. Hindelang, T. Haustein, W. Zirwas, **SC-FDMA Waveform Design, Performance, Power Dynamics and Evolution to MIMO**, Proc. IEEE Portable, March 2007.
2. [V. Jungnickel](http://www.mk.tu-berlin.de/mitarbeiter/tub/lehrbeauftragte/Jungnickel), L. Grobe, **Localized SC-FDMA with Constant Envelope**, Proc. Int. Symp. Personal, Indoor and Mobile Radio Systems (PIMRC), IEEE, London, UK, Sept. 2013, pp. 24-29.

### Unipolar modulation (optional)

To modulate the intensity of light, the signal needs to be real-valued and non-negative. For adaptive OFDM, besides the Hermitean symmetry operation described in subsection 3.2.2.1, a DC bias has to be added, which results in a reduced power efficiency.

#### ACO-OFDM

One way to overcome this disadvantage is asymmetrically-clipped optical (ACO) OFDM as a first unipolar modulation scheme to improve the power efficiency [F-5].

For ACO-OFDM, the time domain signal is made unipolar by simply clipping the negative part at the zero level, which does not need a large DC bias. That is

where *x (k)* is the bipolar real-valued OFDM signal after the IFFT and *xclipped(k)* the unipolar signal after clipping.

If only the odd subcarriers are modulated by signals, the effect of clipping is that inter-carrier interference (ICI) is created that falls only on the even subcarriers. The effect of clipping on the odd subcarriers is simply a multiplication of these components by a constant 0.5. I.e., clipping does not result in inter-carrier interference (ICI) on the odd subcarriers, if the even subcarriers remain vacant. The diagram of ACO-OFDM modulation is shown in Figure 3‑8.

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| --- |
| Figure 3‑9 ACO-OFDM modulation |

[F-5] Xingxing Huang, Siyuan Chen, Zhixin Wang, Jianyang Shi, Yiguang Wang, Jiangnan Xiao and Nan Chi, “2.0-Gb/s visible light link based on adaptive bit allocation OFDM of a single phosphorescent white LED,” IEEE Photonics Journal 7(5), October 2015.

t.b.d.

#### eU-OFDM

A real-valued OFDM signal, generated at the PHY layer, is used to modulate the light. The modulation is conducted only within the active operational range of the device. In this range, the electrical signal and the light output signal cannot be negative at all times. The conventional approach is to set a positive operating point, around which the bipolar OFDM signal can be realized. Figure 4‑9 (left) illustrates this principle. The positive bias can be introduced as part of the analog front-end (in the case of AC-coupled LED drivers) or as part of the information signal (in case of DC-coupled drivers). This approach is known as DC-biased optical OFDM (DCO-OFDM).

Enhanced unipolar OFDM (eU-OFDM) is an optional alternative modulation scheme. It turns the bipolar OFDM signal into a strictly unipolar information signal without the addition of an energy intensive DC component that carries no additional information, see Figure 4‑9 (right).

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| Figure 3‑10 Left: Frame start using DC-biased optical OFDM (DCO-OFDM). Right: Same using Enhanced Unipolar OFDM (eU-OFDM) |

##### Enhanced unipolar OFDM signal generation

The eU-OFDM signals are generated in layers, indicated by the variable STR.

###### One stream

For one stream, i.e. STR = '00', two consecutive copies of every OFDM symbol are created. The polarity of the samples in the second copy is inverted, and finally, all negative samples in the resulting time-domain double-symbol are set to zero. Any time-domain oversampling and pulse shaping is done after the removal of negative samples. The resulting positive signal is used to modulate the transmitter. The concept is illustrated in Figure 4‑10.

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| Figure 3‑11 Unipolar OFDM signal generation (one stream). |

###### Two streams

For two streams, STR = '10', every three OFDM symbols are grouped into one eU-OFDM block, where the first two symbols are assigned to stream 1 (St1) and the remaining single symbol is assigned to stream 2 (St2).

The first two symbols in St1 are modulated using the algorithm described for STR='00' and shown in Figure 4‑10. The single symbol in St2 is modulated in a similar manner, but instead of two copies, four consecutive copies are created for the OFDM symbol in St2, where the first two copies are kept unchanged, while the polarity of the samples in the next two copies is inverted.

Following this procedure, all negative samples in both St1 and St2 are removed, and the two signals are summed up. Any time-domain oversampling and pulse shaping is done after the removal of the negative samples. The resulting positive signal can be used to modulate the transmitter.

###### Three streams

For three streams, i.e. STR = '01', every seven OFDM symbols are grouped into an eU-OFDM block, where the first four symbols are assigned to data stream 1 (St1), the next 2 symbols are assigned to data stream 2 (St2) and the last symbol is assigned to data stream 3 (St3).

The four symbols in St1 and the two symbols in St2 are modulated using the algorithm described for two streams, see 4.2.4.2.1.2. The symbol in St3 is modulated in a similar manner, however, eight consecutive copies of that symbol are generated, where the first four copies are left unchanged, while the polarity of the samples in the following four copies is reversed.

Following this procedure, all negative samples in St1, St2 and St3 are removed. Any time-domain oversampling and pulse shaping is done after the removal of the negative samples. The signals in the three streams are summed up and the resulting positive signal can be used to modulate the transmitter.

###### Four streams

For four streams, i.e. STR = '11', every fifteen OFDM symbols are grouped into an eU-OFDM block, where the first eight symbols are assigned to data stream 1 (St1), the next four symbols are assigned to data stream 2 (St2), the following two symbols are assigned to data stream 3 (St3) and the last symbol to data stream 4 (St4).

In the first stream, two consecutive copies of every OFDM symbol are transmitted, where the second copy is multiplied by -1. In the second stream, four consecutive copies of every OFDM symbol are transmitted, where the first two copies are transmitted in their original format, while the signs of the third and the fourth copy are multiplied by -1. In the third stream, eight consecutive copies of every OFDM symbol are transmitted, where the first four copies are conveyed in their original format, while the signs of last four copies are multiplied by -1. In the fourth stream, sixteen consecutive copies of the single OFDM symbol are transmitted, where the first eight copies are used in their original format, while the last eight copies are are multiplied by -1.

Finally, all negative samples in the four streams are removed and the signals from the four streams are summed up. Any oversampling and pulse shaping is done after the removal of the negative samples. The resulting positive signal can be used to modulate the transmitter.

###### Notes on the receiver algorithm

In order to demodulate the data encoded in the first stream (St1), the samples in every even OFDM symbol interval are subtracted from the samples in every odd OFDM symbol interval. For example, the samples in the second symbol are subtracted from the samples in the first symbol, the samples in the fourth symbol are subtracted from the samples in the third symbol, etc. Note that due to the structure of the other data streams (St2 up to St4), the subtraction operation completely removes interference from these streams.

After the subtraction operation, the resulting data at St1 can be demodulated using the conventional OFDM demodulator algorithm. After the data in St1 are demodulated, the stream is re-modulated again and subtracted from the overall received signal.

Following the subtraction of the re-modulated St1 signal, all frame copies at St2 which were originally identical (the symbols in question are the symbols that have identical polarity) should be summed up. For example, the first and the second symbols should be summed, the third and the fourth symbols should be summed, the fifth and the sixth symbols frames should be summed, etc. The resulting signal at St2, then, has the same format as the signal at St1. Hence, it can be demodulated after each even symbol is subtracted from each odd frame. Upon demodulation, the resulting bits can be re-modulated and the resulting waveform can be subtracted from the overall received waveform as in the case for St1. The procedure is re-iterated for the remaining streams up to St4 (depending on the configuration) until all data bits are recovered.

### Multiple-input multiple-output

The use of several multiple-input multiple-output (MIMO) schemes is foreseen in order to support diversity and spatial multiplexing, which can both be realized both as non-imaging and imaging MIMO [F-6, F-7]. The performance of wavelength-division multiplexing (WDM) and wavelength-shift keying (WSK) transmission can also be improved by using MIMO transmission schemes.

#### Signal model

For two transmitters and two receivers, the signal model for non-imaging MIMO transmission on each sub-carrier can be expressed as

where, in general, bold upper case letters describe matrices and bold lower case letters describe vectors. The received signals are denoted as *y~~i~~* where *i=1…nRx* and *nRx* is the number of receivers. The transmitted signals are described as *x~~j~~* where *j=1…nTx* and *nTx* is the number of transmitters. The channel matrix elements *Hij* represent the channel gain from the *jth* transmitter to the *ith*receiver.

#### Non-imaging MIMO

In case of non-imaging MIMO, see Figure 3‑9, light from each of all transmitters (usually having a wide beam) is received by all receivers (usually having wide field-of-views, FOV) , but channels may have different path loss and impulse response as shown in Figure 6. In case of non-imaging MIMO, the channel matrix ***H*** is usually fully occupied and the elements *Hij* may depend on the subcarrier index *n* because of the frequency response of optoelectronic components and the superposition of LOS and NLOS propagation effects.

|  |
| --- |
| Figure 3‑12 Non-imaging MIMO transmission |

#### Imaging MIMO

Imaging MIMO uses imaging optics between the transmitters and receivers, which are usually arranged in arrays. Because of the lens, the LOS component is often dominant while the diffuse reflections are reduced due to the reduced FOV at the receiver. Ideally, the transmitzter array is imaged 1:1 onto the receiver array. In this case, the channel crosstalk can be neglected, and the channel matrix ***H*** has a diagonal shape, i.e. can be simplified and becomes diagonal, i.e.

|  |
| --- |
| Figure 3‑13 Imaging MIMO transmission |

#### Polarization-division multiplexing

Lights emitting from incoherent LEDs include all polarization directions that can be decomposed as two orthogonal bases, e.g. of horizontal (h) and vertical (v) polarization. For LED-based polarization-division multiplexing (PDM), a linear h-polarizer is inserted that can only allow h-polarized components passing through at the first transmitter (TX1); meanwhile, a linear v-polarizer is used at TX2. Note that many laser diodes yield linearly polarized light so that the transmitter-sided polarizers may not be needed when using lasers. After passing through Tx- sides polarizers, the polarized light is mixed up after free-space propagation. At the receiver (RX), two polarizers are then implemented to filter out the unwanted polarized lights, thus obtaining the transmitting signals.

|  |
| --- |
| Figure 3‑14 Polarization-division multiplexing |

#### Wavelength-division multiplexing

t.b.d.

#### Link setup for MIMO

Initial link setup and header transmission detection are performed in the single-input single-output (SISO) mode, in order to improve the reliability of transmission. Transmission of the preamble and the header is done using all transmitters, while detection can be improved by using maximum ratio combining (MRC) based on individual estimates of the superimposed channels from all transmitters at each receiver . [[5]](#footnote-5) The number of used transmitters is included in the header.

#### Additional channel estimation symbols for MIMO

Additional channel estimation (ACE) symbols are sent in the beginning of the data field in the PHY frame. They are defined in the frequency domain and over multiple OFDM symbols. Each ACE symbol contains the same sequence of bits on all subcarriers that is only passed through the constellation scrambler. For MIMO, the sequence {sn} contains all 1s, but is multiplied as a whole with a sign taken out of an orthogonal sequence.[[6]](#footnote-6) For 1 transmitter (Tx), the channel estimation symbol in the preamble is used

* 1 Tx: [{sn}]

For 2 Txs, the first symbol and one ACE signal are sent as[[7]](#footnote-7)

* 2 Txs:
  + Tx1 [{sn} {sn}],
  + Tx2 [{sn} {-sn}].

where the first symbol is always contained in the header and only one additional symbol is sent for ACE. The scheme in G.9963 obviously makes use of the Hadamard sequences. It can be easily extended to 4 and 8 transmitters

* 4 Txs:
  + Tx1 [{sn} {sn} {sn} {sn}]
  + Tx2 [{sn} {-sn} {sn} {-sn}],
  + Tx3 [{sn} {sn} {-sn} {-sn}],
  + Tx4 [{sn} {-sn} {-sn} {sn}].
* 8 Txs:
  + Tx1 [{sn} {sn} {sn} {sn}{sn} {sn} {sn} {sn}]
  + Tx2 [{sn} {-sn} {sn} {-sn}{sn} {-sn} {sn} {-sn}],
  + Tx3 [{sn} {sn} {-sn} {-sn}{sn} {sn} {-sn} {-sn}],
  + Tx4 [{sn} {-sn} {-sn} {sn}{sn} {-sn} {-sn} {sn}].
  + Tx5 [{sn} {sn} {sn} {sn}{-sn} {-sn} {-sn} {-sn}]
  + Tx6 [{sn} {-sn} {sn} {-sn}{-sn} {sn} {-sn} {sn}],
  + Tx7 [{sn} {sn} {-sn} {-sn}{-sn} {-sn} {sn} {sn}],
  + Tx8 [{sn} {-sn} {-sn} {sn}{-sn} {sn} {sn} {-sn}].

#### Adaptive MIMO transmission

In the following, several transmission modes will be described that can be used to operate a MIMO link. The main objective is to enable a dynamic tradeoff between spatial diversiy and spatial multiplexing, so that the best number of streams is always selected to maximize the throughput and to operate the link reliably. It is assumed that the MIMO link will be operated adaptively in a bidirectional closed-loop manner and that MIMO metrics reports regarding the forward link are provided over the reverse link.

##### Optimal MIMO transmission

Ideally, with having full channel state information conveyed from the receiver to the transmitter, the MIMO transmission can be described as follows. The transmission on each subcarrier is most conveniently formulated in the frequency domain as



where the (*nTx* ×1) vector **x***n* contains the signals transmitted from all transmitters at the OFDM sub-carrier with index *n*. The (*nRx* × 1) vectors **y***n* and **ν***n* contain the received signals and the noise, respectively. The integers *nTx* and *nRx* denote the numbers of transmitters and receivers, respectively.

The (*nRx* × *nTx*) matrix **H***n* denotes the channel matrix for sub-carrier *n* with the channel coefficients between each transmitter and each receiver. It is related to the time-domain channel impulse response matrices **H***l* as



where *L* denotes the number of resolved multi-paths. In the optimal way, based on full channel state information (CSI) at the transmitter and at the receiver, the channel capacity is approached asymptotically by performing a singular value decomposition (SVD) of **H***n*on each sub-carrier,



which gives the matrices **V***n* and **U***n* containing the Eigenvectors of the channel matrix in the transmit and receive spaces, respectively.

The diagonal matrix **D***n* which contains *i*= 1…min(*nTx*, *nRx*) singular values , referred to as the amplitude gains of the spatial Eigenmodes. The superscript *H* denotes the conjugate transpose of a matrix. In the information theory, the capacity is asymptotically approached for infinite *N* by a joint water-filling across all spatial Eigenmodes *i* and all sub-carriers *n*. Unlike in the information theory, in practise we employ discrete instead of continuous modulation alphabets. A joint bit-loading and power allocation algorithm is therefore used with individual modulation on each Eigenmode and each sub-carrier, according to the current channel state, so that important optimization criteria (throughput, fairness, stability of queues) can be fulfilled.

The transmitted signal vector **x**n**=V**n**d**n is obtained from the data vector **d**n and the spatially multiplexed data signals are reconstructed at the receiver as . The noise in each stream is boosted differently, according to the singular value for each stream.

Depending on the availability of the CSI, there are modifications. When CSI is available only at the receiver, no pre-processing is applied. Assuming additionally linear detection which requires a simple matrix-vector multiplication, the transmitted signals on each sub-carrier may be reconstructed using the minimum mean-square error detector given by the formula



where **I** and σ² are the (*nTx* × *nTx*) identity matrix and noise variance at one receiver, respectively.

|  |
| --- |
| Figure 3‑15 – Adaptive MIMO transmission. |

##### Practical implementation

Following the optimal MIMO transmission scheme, spatial processing is introduced both at the transmitter and at the receiver, see Figure 8. Moreover, a variable number of streams is used because in some cases, depending on the time-variant wireless channel, a higher capacity is reached with a reduced number of streams. For instance, if an LED is directed away from the receiver, it is hardly useful for transmission and may be switched off.

User data are de-multiplexed yielding Q parallel data streams, where Q is an integer ranging from 1 to *nTx*. The data in each stream are transported using an individually selectable modulation scheme on each subcarrier, in order to maximize the throughput, which is also denoted as per-stream rate control. All active streams are then passed through a spatial scheme processing unit, in which channel knowledge, obtained over the reverse link is used to identify the best spatial pre-processing of all streams transported in parallel. It is clear that the MIMO channel rank can vary over time and also as a function of the subcarrier index *n*. Accordingly, and as a natural extension of the adaptive OFDM approach, the selection of the best MIMO transmission mode is done for each subcarrier or for a group of subcarriers. Several simplifications of the spatial processing are introduced now in order to reduce complexity.

##### MIMO transmission modes

1. **Spatial repetition code:** One important simplification is that only one stream is transmitted and received over all LEDs and PDs, respectively. This mode is useful, e.g., in order to create an omnidirectional transmitter characteristics. This can be reached using the precoding vector **v**n = (1 1 1 1 …1)T.
2. **Transmitter selection:** In order to save energy, modulation may be switched off for some LEDs, which results in zeros at the respective positions in the precoding vector **v**n.
3. **Receiver selection:** As only one stream is transmitted using multiple LEDs, maximum ratio combining (MRC) is optimal. However, it requires an ADC at each receiver as well as multiple FFTs. Often, few links in the MIMO channel have free LOS and a reduced path loss, accordingly, and for all modulation frequencies. Hence, the channel matrix is “sparse”. For reduced complexity, it may be sufficient to select the strongest received signals and to combine them using equal gain combining (EGC). This can be realized already in the analog domain so that fewer ADC are sufficient.
4. **Combined transmitter and receiver selection:** There can be a combination of transmitter and receiver selection.
5. **Transmitter and receiver selection for multiple streams:** The above two schemes can even be combined with multi-stream transmission as long as the number of streams Q is equal or smaller than the minimum of the numbers of active transmitters and receivers. At the receiver side, the residual cross-talk is then reduced by multi-stream processing.
6. **WDM transmission:** For WDM, because different colors are used, normally the number of streams is the same as the number of transmitter ports. In this case, multiple streams are transmitted in parallel and the precoding matrix on all subcarriers is given by **V**n = **1**n.Because color separation behind the receiver filters may be imperfect, MIMO reference symbols can be transmitted, and MIMO channel estimation and processing can be performed in order to reduce the residual cross-talk and to increase the spectral efficiency.
7. **WSK transmission:** For WSK transmission, e.g. in case of an RGBY LED, the precoding vector **v**n = (aR aG aB aY)T is used. If MIMO reference symbols are transmitted, imperfect color calibration at the transmitter, which could also be falsified by reflecting surfaces, can be compensated by MIMO processing at the receiver side.

### Coordinated wireless network

The idea of the coordinated wireless network (COW) is to deploy multiple APs so that continuous coverage is reached for mobile optical wireless user devices in a desired service area. There may be overlapping coverage areas, where horizontal handover from one AP to another AP is needed and non-overlapping areas, where vertical handover to another wireless technology is needed. In the following, the overlapping case is described.

#### Link setup for COW transmission

Same as in the MIMO mode, initial link setup and header transmission detection are performed in the single-input single-output (SISO) mode, in order to improve the reliability of transmission. Transmission of the preamble and the header is done over all transmitters of all APs. Channel estimation symbols used by different APs are made orthogonal to each other.[[8]](#footnote-8) Header detection can be improved by using maximum ratio combining (MRC) based on individual estimates of the superimposed channels from all transmitters at each receiver . A list of APs in the jointly served area is included in the header, together with the assigned comb shift, see 4.2.6.2. As described below, the list can include spatial reuse of comb shifts for multiple APs.

|  |
| --- |
| Figure 3‑16 – Additional channel estimation symbols used in the coordinated wireless network. Center: Over multiple ACE symbols, each LED at a given access point transmit another sequence. Subcarriers marked with the same color are assigned to the same access point. Subcarrier combs can be reused after a certain distance. The assignment of ACE symbols can be defined and changed dynamically by the network management, e.g. if a new AP is added to the network. |

#### ACE symbols for COW transmission

In order to identify different APs in the COW topology and to maintain the possibility to use MIMO at each AP, channel estimation symbols for different APs are made orthogonal in the frequency domain. The general idea is that, during the entire channel estimation block, each AP is assigned another comb of subcarriers (marked with the same specific color in Figure 7), from a set of orthogonal combs [11].

Using a comb of subcarriers only, instead of all subcarriers, is possible because only as many subcarriers are needed for channel estimation as there are taps in the CP, in order to identify all multi-paths. Advanced and computationally efficient algorithms are available in the literature in order to accurately interpolate the channel frequency response based on such subcarrier combs [12]. Note that the same comb can be reused by APs after a certain distance, at which the signal is sufficiently attenuated.

The comb scheme can be extended to MIMO. Based on the comb symbols used for COW transmission, the same rules are applied as for single-cell MIMO, see 4.2.5.7.

#### Cell- and user-specific ACE

Note that ACE signals are sent twice in the COW topology. In the first period, also denoted as cell-specific AC (CS-ACE), the ACRE sequence is sent directly from all transmitters, so that the physical channel matrix ***H*** is estimated on each subcarrier. This information is useful for joint transmitter optimization, after the AP received the estimated CSI via feedback from its UDs.

In the second period, also denoted as user-specific ACE (US-ACE), the ACE sequence is passed though the transmitter optimization, before being transmitted. Note that the joint transmitter optimization depends on the channel of other UDs attached to other APs as well. Only by using US-ACE, the UD can estimate the modified effective channel matrix ***H***effective and adapt its receiver processing, accordingly.

#### Adaptive COW transmission

t.b.d.

### Relaying

Relaying operation supports half duplex (HD) and full duplex (DF) duplexing modes as well as amplify and forward (AF) and decode and forward (DF) relaying modes.

#### Full duplex (FD) Mode

In FD relaying mode, the REL simultaneously receives and transmits both in uplink and downlink supporting the AF mode. The method is proprietary.

#### Half duplex (HD) relaying

In HD relaying mode, the relay REL shall decode and store the data packets in order to retransmit them to the REL in its transmission period supporting the DF mode. The REL can erase the stored packet after it receives the ACK. The method is proprietary.

### Payload data

In front of the OFDM modulator (and an eventual preprocessing to generate single-carrier and unipolar signals), payload data are scrambled and then fed into the forward error correction (FEC). Next they are mapped onto constellation points. Finally there is an additional constellation scrambling operation.

#### Data scrambling

For data scrambling, a linear feedback shift register (LSFR) is used. It is defined by the number of registers NLFSR. The position of feedback taps is commonly described via a generator polynomial and the initialization of the registers s1 to sNLFSR.

In Figure 2‑8 the LFSR used for data scrambling is shown. It implements the generator polynomial and its register range from s1 to s23.



Figure 3‑17 – LFSR for data scrambling

All data starting from the first bit of the PHY-frame header (PFH) and ending by the last bit of the payload shall be scrambled with a pseudorandom sequence generated by this LFSR.

The LFSR generator is initialized at the first bit of the header with the initialization vector equal to 0x2AAAAA in hexadecimal notation or 0010 1010 1010 1010 1010 1010 in binary notation where the LSB corresponds to C1. This initialization is used for the scrambling of the header data. The first bit to be scrambled shall be XOR'ed with the first bit generated by the LFSR after initialization (i.e., C18 XOR C23 of the initialization vector).

The special value for SI (scrambler initialization) in the PHY-frame header of 016 in hexadecimal notation indicates that the scrambler is not re-initialized between the header and the payload. An initialization of the SI field to values other than the special value is optional, as described in the G.hn specification.

#### Forward-error correction

##### Channel coding for the header

Channel coding for the header uses low-density parity-check codes (LDPC) according to the G.hn standard, see [4]. A short LDPC code of K=168 data bits with code rate ½ is used. The resulting block is modulated with QPSK with repetitions in frequency. If bandwidth is low and SNR shall be increased, the header symbol can be repeated in time.

|  |
| --- |
| Figure 3‑18 The low-density parity check code from the G.hn standard is used. |

##### Channel coding for the data

Channel coding for the data uses LDPC according to the G.hn standard, see [4]. The LDPC code may be selected between two information block sizes of 4320 or 920 bits bits and 5 code rates of 1/2, 2/3, 5/6, 16/18 or 20/21.

##### Channel coding for MIMO

Stream-interleaved encoding is used, consistent with the G.hn standard. Stream-wise decoding is not considered, as it would increase both, complexity and latency. To be further detailed.

t.b.d., see G.9960-2015

#### Bit-to-Symbol Mapper

t.b.d., see G.9960-2015

#### Constellation Scrambling

In Figure 2‑9 the LFSR used for the constellation scrambler is shown. It implements the generator polynomial and its registers range from s1 to s13 being the least significant bit (LSB) and most significant bits (MSB), respectively.



Figure 3‑19 – LFSR for constellation scrambling

The phase of the complex symbols generated by the bit-to-symbol mapper is shifted before being fed into the IFFT. The phase shifts are determined by the pseudo-random bit-sequence generated by the LSFR depicted in Figure 2‑9. The two LSBs s1 and s2 determine the shift as given by Table 2‑1. For a generated phase shift , the LSFR is shifted by . Due to the constellation scrambling, the phase of an originally generated complex symbol is shifted by resulting in , the actual input of the IFFT:

.

Table 2‑1 – Phase shift values from LFSR states s1 and s2

|  |  |  |
| --- | --- | --- |
| **Register states of the LFSR** | | **Phase shift** |
| s2 | s1 |  |
| 0 | 0 |  |
| 0 | 1 |  |
| 1 | 0 |  |
| 1 | 1 |  |

For the header, ACE and payload, the shift of the -th subcarrier is and therefore the LSFR is shifted by for each subcarrier. For these cases, the LSFR is initialized to the seed of 1FFFF16 in hexadecimal notation for each OFDM symbol, where the LSB of the seed corresponds to s1.

# PHY Layer Dimming Method

**Dear Proposer: in this section we need you to describe your dimming method. If you proposed one or more OCC PHY modes that support dimming than please write a paragraph to describe how the dimming works. You may include figures and drawings as needed.**

**< Enter paragraph here >**

FFS

# PPDU format

**Dear Proposer: for each of the PHY modes of interest, please describe to the best of your ability your envisioned PPDU format. You can take the present PPDU and modify it accordingly. If possible, describe what you envision for each of the PPDU fields.**

## Frame structure

The data signal, denoted as payload in Figure 4‑1, is transmitted together with additional signals in a compound frame, so that the payload can be decoded frame-wise. The preamble is followed by a PHY header. The preamble allows coarse time synchronization in its first two parts, followed by a reference sequence used for fine timing as well as channel estimation, what enables the receiver to decode the header information. After the header, eventually there are additional channel estimation (ACE) symbols, basically needed for the support of multiple-input multiple-output (MIMO), before the payload is then transmitted. In case of using MIMO in 802.15.7r1, all transmitters transmit the same preamble and header information, while only the payload makes explicit use of MIMO. The ACE symbols contain an orthogonal sequence of symbols (same symbols but with alternate signs) in order to estimate the MIMO channel.

|  |
| --- |
| Figure 5‑1 – P2P PHY frame, taken over from G.hn specification. |

### Frame types

By using the same frame structure, the PHY can transport different frame types. An overview is provided in Table 4‑1.

Table 4‑1 –PHY frame types. The basic frame types are highlighted using bold letters.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Frame type** | **Frame type (FT)** | **Description** | **Header** | **Payload** | **Duration indicator**  **(DRI)** | **Ext. Header indicator** |
| **MAP/ RMAP** | 0000 | A frame carrying the medium access plan (MAP) or relayed MAP (RMAP) where the payload contains a MAC Protocol Data Unit (MPDU) | Yes | Yes | 1 | 0 |
| **MSG** | 0001 | Data and management frame, carrying user data or management data or both; the payload contains an MPDU | Yes | Yes | 1 | 0 |
| **ACK** | 0010 | acknowledgement (ACK) control frame, the relevant ARQ data is communicated in the header | Yes | No | 0 | 0 or 1 |
| RTS | 0011 | A request-to-send control frame; the relevant data is communicated in the header | Yes | No | 1 | 0 |
| CTS | 0100 | A clear-to-send control frame; the relevant data is communicated in the header | Yes | No | 1 | 0 |
| CTMG | 0101 | Sort control frame, carrying a short control message | Yes | No | 0 | 0 or 1 |
| **PROBE** | 0110 | A frame carrying probe symbols in its payload | Yes | Yes | 1 | 0 |
| ACKRQ | 0111 | An ACK retransmission request frame; the relevant data is communicated in the header | Yes | No | 0 | 0 |
| BMSG | 1000 | A bidirectional MSG frame, it  contains data and management frames in the payload and ACK | Yes | Yes | 1 | 0 or 1 |
| BACK | 1001 | A bidirectional ACK frame,  contains ACK and data and management frames in the payload | Yes | Yes | 1 | 0 or 1 |
| ACTMG | 1010 | An acknowledgment frame for a control message (CTMG) frame | Yes | No | 0 | 0 |
| Reserved | 1011 to 1110 | Reserved frame types |  |  |  |  |
| FTE | 1111 | Frame Type Extension, pointer to a set of additional frame types | Yes | No | 0 or 1 | 0 or 1 |

### Preamble

The preamble is prepended to a PHY frame and is intended for frame detection/synchronization, initial channel estimation and OFDM symbol alignment. It may be used for recovery of the following header segment of the PHY frame.

The preamble is divided into three sections; each consists of a repetition of OFDM symbols , where the subscript denotes the section. Each is output by the IFFT. The inputs of the IFFT, i.e. complex valued symbols, are generated by feeding into the constellation scrambler described in 2.2.2.7.2 a constant series of 1s. The three sections are windowed and combined additively as outlines in Figure 4‑2.



Figure 5‑2 – Preamble structure

In the default case, every -th subcarrier is used, starting from the subcarrier index . For , the used subcarrier spacing and the LSFR seed differs from the cases in which as described in Table 4‑2.

Table 4‑2 – Default properties of preamble sub-sequences

|  |  |  |  |
| --- | --- | --- | --- |
| **property** | **Section 1** | **Section 2** | **Section 3** |
| OFDM symbol |  |  |  |
|  | 10 | 4 | 2.5 |
|  | 4 | 4 | 1 |
| LFSR seed | 16E616 | - | 110516 |

An alternative subcarrier starting index and for the use of cell specific preambles is still open for discussion.

### Channel estimation

The final OFDM symbol in the preamble is used for channel estimation. It is useful to detect the header information and when using single-input single-output (SISO) transmission, it can also be used for the detection of data. In case MIMO is used additional channel estimation (ACE) symbols are used for channel estimation. These additional symbols are sent after the header, as part of the data block in the frame.

### PHY frame header

The PHY-frame header always fits into an integer number of OFDM symbols and is transmitted using a single, predefined set of modulation and coding parameters. i.e. 1 bit/symbol with code rate ½. The core part of the PHY-frame header is 168 bits long. It is composed of a common part and a variable part. The fields of the PHY-frame header are defined in the following table.

|  |  |  |  |
| --- | --- | --- | --- |
| **Field** | **Octet** | **Bits** | **Description** |
| **Common Part** | | | |
| FT | 0 | [3:0] | Frame type |
| DOD | [7:4] | Domain ID |
| SID | 1 | [7:0] | DEVICE\_ID of the source node |
| DID | 2 | [7:0] | DEVICE\_ID, MULTICAST\_ID or BROADCAST\_ID of the destination node(s) |
| MI | 3 | [0] | Multicast indication identifying whether the DID is a unicast or multicast destination |
| DRI | [1] | Duration indication identifying whether FTSF starts with a 16-bit duration field |
| EHI | [2] | Extended header indication |
| HSI | [3] | Header segmentation indication |
| Reserved | [7:4] | Reserved (zero if not used) |
| **Variable Part** | | | |
| FTSF | 4 to 18 | [119:0] | Frame-type specific field |
| **Common Part** | | | |
| HCS | 19+20 | [15:0] | Header check sequence |

The common part contains fields that are common for all PHY-frame types. The variable **frame-type specific field (FTSF)** part contains fields according to the PHY-frame type. The content of the core part is protected by the 16-bit header check sequence (HCS).

#### Common part fields of the PHY-frame header

The **frame type (FT)** field is a 4-bit field that indicates the type of PHY frame.

The **domain ID (DOD)** field contains the domain ID to which the source and destination devices of the PHY frame belong. It is represented as a 4-bit unsigned integer with valid values in the range from 0 to 15. Value 0 is a special value reserved for inter-domain communication.

The **destination ID (DID)** field identifies the destination node(s) of the PHY frame. It is represented as an 8-bit unsigned integer with valid values in the range from 0 to 250.

If the **multicast indication (MI)** bit is set to zero, the DID field shall contain the DEVICE\_ID of the destination node (for unicast transmission). If the MI bit is set to one, the DID field shall contain a MULTICAST\_ID or BROADCAST\_ID of the destination nodes.

If the **duration indication (DRI)** bit is set to zero, the PHY frame shall not contain any payload (i.e., contains only preamble and PHY-frame header). If the DRI bit is set to one, the FTSF shall start with a duration field. The duration field contains the duration of a single PHY frame or PHY frame sequence. It shall be represented as a 16-bit unsigned integer with valid values in steps of 0.25 μs. It shall be the smallest integer larger than or equal to the actual duration.

If the **extended header indication (EHI)** field is set to zero, the PHY-frame header shall contain 168 information bits. If it is set to one, the PHY frame header shall contain 2×168 information bits. The EHI field shall be set according to the frame type as shown in Table 4‑1.

The **header check sequence (HCS)** field is intended for PHY-frame header verification. It is a 16-bit cyclic redundancy check (CRC) and shall be computed over all the fields of the PHY-frame header in the order they are transmitted, starting with the LSB of the first field of the PHY frame header (FT) and ending with the MSB of the last field of the FTSF. The HCS is computed using the following generator polynomial of degree 16

*G*(*x*) = *x*16 + *x*12 + *x*5 + 1

The value of the HCS is the remainder after the contents (treated as a polynomial where the first input bit is associated with the highest degree, X168–17, where 168 is the header length in bits, and the last input bit is associated with X0 of the calculation field is multiplied by *x*16 and then divided by *G*(*x*). The HCS field is transmitted starting with the coefficient of the highest order term.

#### Variable part fields of the PHY-frame header

The ITU-T recommendation G.9960-2015 contains a very detailed description of the variable frame-type specific field (FTSF) in the PHY-frame header. Here, only the main parameters in each frame type are explained.

The **medium access plan (MAP)** and **relayed MAP (RMAP)** PHY frames are used to schedule transmission opportunities among the devices in a direct or relayed transmission. The FTSF of MAP and RMAP frames contains the duration of the MAP frame, the network time reference, i.e. the start of the first OFDM symbol of the preamble with 10 ns resolution. The start time of the next MAC cycle, the size of repetition blocks, scrambler initialization value, the information block size of the FEC code word used for the payload, the number of repetitions used for encoding the data, the concatenation factor in the FEC, the band plan which contains the used bandwidth for this frame. The MAP type indicates what kind of bit allocation table is used for the bitloading of the payload. Finally, the type of MAP or RMAP transmission is indicated and the number of hops from the master domain.

The **data and management frame (MSG)** is usedto carry user data or management data or both. The parameters in the MSG frame are the duration of the MSG frame, the information block size of the payload, code rate, number of repetitions, concatenation factor, scrambler initialization, and if a master is detected or not. Next there are the identifier of the bit allocation table, either the band plan (for uniform number of bits loaded) or the subcarrier grouping used for the bit loading, what cyclic prefix is used, a connection identifier, whether or not an acknowledgement reply is required, the number of the PHY frame in a burst frame and the burst end flag. An important number for the use of MIMO is the number of additional channel estimation symbols (ranging from 0 to 7). Notice also the important connection management field, by which connections can be initialized or released, with or without acknowledgement but always without transporting a payload. Moreover, the MSG frame contains information about the bandwidth reservation, by which the devices get informed about the length of the connection queue, requests for bidirectional transmissions and further information to control the transmission of the payload.

The **acknowledgement frame** **(ACK)** is used to communicate the relevant ARQ data in the header. It contains detailed information for the flow control, requests for bidirectional transmissions, a bad burst indicator, means for channel estimation control, the identifier for the runtime (i.e. time-variant) bit allocation table and a complex field for acknowledgement data depending on whether unicast or multicast is being used. Essentially, this field indicates to the transmitter what segment of a frame was lost. Obviously, that list is being used to control the **selective repeat mechanism**, which is one of the key features in G.hn to reduce the latency and improve the robustness likewise.

The **request-to-send (RTS)** control frame contains specific means to establish the exchange of data. It contains the transmission times of the RTS, CTS and MSG frames, as well as of eventually needed ACK frames and their duration, the device ID of the node that should respond to the request.

The **PROBE** FTSF is composed of a common part and a variable part. The common part contains fields for the duration of the probe frame and its type, containing either silent signals or channel estimation probe symbols, the number of probe symbols, the used probe guard interval and an additional probe frame type specific field.

The **ACK retransmission request (ACKRQ)** frame shall allow the receiver to request retransmission of specific receiver windows for either data or management connections or both. Moreover, there are bidirectional variants of the **bidirectional MSG (BMSG) and ACK (BACK)** frames and an opportunity to add additional frame types by using the **frame type extension (FTE)** and an opportunity to add an **extended header** which is similar to the original frame types while adding further functionalities that the original frames can no longer host. This information is sent in further OFDM symbols immediately after the original header.

#### Bits for signaling of optional modulation schemes

The transmitter signals to the receiver the new transmission PHY mode using the eU and STR bits in the advanced modulation PHY header (These three bits need to be accomodated into the High-speed PHY header). For compliance purposes, the PLCP preamble and the PHY headers are encoded in a DCO-OFDM fashion as described in 3.3 – 3.5.

Following the four BPSK frames containing the PHY header, as well as the *N*MIMO reference symbols when applicable, the data field is encoded in an eU-OFDM fashion ( The header looks differently in the high-speed PHY) (see Fig. 1(b)). The eU-OFDM algorithm works as follows.

# PHY PIB attributes

**Dear Proposer: add any anticipated PHY PIB attributes here**

See IEEE802.15.7-2011 Table 100 for the current PHY PIB Table

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **PHY PIB Table 100 Additions** | | | | |
| **Attribute** | **Identifier** | **Type** | **Range** | **Description** |
|  |  |  |  |  |
|  |  |  |  |  |
|  |  |  |  |  |

# Superframe Structure

**Dear Proposer: if you have an opinion as to the superframe structure then please express your opinion below; otherwise, you can leave this section blank.**

## Duplex mode

FFS

## Superframe

A coordinator on a VPAN can bound its channel time using a superframe structure. The format of the superframe is defined by the coordinator and varies with the network topologies. The superframe is bounded by beacons sent by the coordinator and is divided into equally sized time slots (TS). The duration of the superframe for star and coordinated network topologies shall be fixed and set to Tsuperframe. Each superframe can have two or three portions: beacon period (BP), contention access period (CAP) and optional contention-free period (CFP), as shown in Figure 7‑1.

In peer-to-peer and star topology, the BP shall contain only one beacon slot. In coordinated network topology, the BP consists one to a maximal of MaxBeaconSlot beacon slots. The coordinator transmits a beacon in one of the multiple beacon slots every superframe. The structure of a BP is specified in the beacon frame. The duration of each beacon slot is equal to the sum of the duration of a beacon PPDU and the subsequent beacon-to-beacon interframe space. The beacons are used to synchronize the attached devices, to convey the information and parameters of the VPAN operation (e.g., channel access information).

The CAP shall immediately following the BP and complete before the CFP. If the CFP is zero length, the CAP shall complete at the end of the superframe. The CAP shall be at least aMinCAPLength and shall shrink or grow dynamically to accommodate the size of the CFP. Any device wishing to communicate during the CAP competes with other devices via CSMA/CA.

The CFP may be present in star and coordinated network topologies. For low-latency applications or applications requiring specific data bandwidth, the coordinator is allowed to dedicate portions during the CFP to that application. These portions are called guaranteed time slots (GTSs). The GTSs forms the CFP, which always appears at the end of the superframe starting at a TS boundary immediately following the CAP. More information on the CFP and GTSs is provided in 7.4.1 and 7.6.1. All contention-based transactions shall be completed before the CFP begins. Also each device transmitting in a GTS ensures that its transaction is complete before the time of the next GTS or the end of the CFP.

All transactions are completed by the time of the next beacon.

|  |
| --- |
| Figure 7‑1 An example of the superframe structure of different network topologies |
| Figure 7‑2 An example of the structure of the beacon period |

# MAC frame formats

**Dear Proposer: in the section below you can express your opinion as to the MAC frame format. If you have no opinion then you can leave this section blank.**

## Peer-to-Peer

FFS

## Star

### Channel access

Both contention access and contention-free access shall be supported. Contention-free access shall be used for transmissions of beacon frames and transmissions in GFP. Contention access is based on random access and shall be used for transmissions in CAP. Both data and command frames (e.g., association related command frames) can be transmitted in the CAP.

#### Channel access in CAP

CSMA/CA mechanism is used during the channel access in CAP, which supports prioritized access. To reduce the probability of collisions among contending devices, a random back-off algorithm is used to separate the timing that the different devices attempt to transmit. Prioritized access is achieved by assigning differentiated contention parameters to different access priorities, which allows frames associated with higher access priorities to win the contention with higher probabilities.

In order to handle the hidden node problems, RTS/CTS mechanism may be used during the CAP. The coordinator shall decide and indicate in the beacon if the RTS/CTS protocol can be used in the CAP. The decision on whether the RTS/CTS protocol should be used is out of the scope of this standard.

#### Channel access in CFP

The coordinator can divide the CFP of a superframe into multiple GTSs and assign them to itself or the associated devices which have traffic requiring guaranteed QoS. A device can request GTS allocations through flow establishment procedure, which is controlled by the coordinator and specified in clause 5.4.5.

The coordinator shall distribute the GTS allocations to devices via the beacon frame. The GTS descriptor shall include the basic parameters and information, such as the length and position of the GTS and the device assigned to the GTS. The GTS descriptor may supply additional information, such as the subcarriers/frequencies/wavelengths that the device is allowed to use in the GTS, which can be used in the case that the interference coordination between different VPANs is needed.

### VPAN establishment

#### Scanning procedures

All devices shall be capable of performing scanning procedures which allows the device to discover VPANs operating in its vicinity. A device is instructed to begin a scan through the MLME-SCAN.request primitive. The results of the scan shall be returned via the MLME-SCAN.confirm primitive.

#### Establish a VPAN

Establishing a new VPAN shall start with resetting the MAC sublayer and the PHY layer. The next higher layer of the prospective coordinator shall isuss a MLME-RESET.request primitive to its MLME. The MLME turn off the transceiver by issuing a PLME-SET-TRX-STATE.request to the PHY layer, and then the MAC sublayer is set to its initial conditions, clearing all internal variables to their default values.

The MLME of the prospective coordinator shall respond with a MLME-RESET.confirm primitive to notify the next higher layer the result of the reset operation.

After the reset, the next higher layer of the prospective coordinator shall issue a MLME-SCAN.request primitive to require the MLME to perform a scan to discover other VPANs by obtaining their corresponding beacon frames. The MLME shall perform the scan and report the result of the scan to its next higher layer with a MLME-SCAN.confirm primitive.

After the scan, the next higher layer shall choose a VPAN ID for the new VPAN. The next higher layer provide the new VPAN ID along with other parameters to the MLME by issuing a MLME-START.request primitive. On receipt of MLME-START.request primitive, the MLME shall begin to send beacon frames and operate as a coordinator and the VPAN is established.

### Association and disassociation

#### Association

A device shall perform a passive scan procedure (see clause 5.4.2.1) after it is powered on to locate any coordinator transmitting beacon frames within its coverage area. The results of the channel scan would have then been used for choosing a suitable VPAN. The algorithm for selecting a suitable VPAN with which to associate from the list of VPAN descriptors returned from the channel scan procedure is out of the scope of this standard.

Following the selection of a VPAN with which to associate, the next higher layers shall request through the MLME-ASSOCIATE.request primitive that the MLME configures the PHY and MAC PIB attributes to the values necessary for association.

A coordinator shall allow association only if macAssociationPermit is set to TRUE. Similarly, a device should attempt to associate only with a VPAN through a coordinator that is currently allowing association, as indicated in the results of the scanning procedure. If a coordinator with macAssociationPermit set to FALSE receives an association request command from a device, the command shall be rejected.

The device shall synchronize to the VPAN that it will associate with, and initiate the association procedure by sending an association request command.

Upon the reception of the association request command, the coordinator shall determine if it will accept the association request and reply an association response command to the device within TBD ms. The coordinator shall indicate if it accepts the request in the association response command, and if it denies the request, it shall also indicate the reason. If the coordinator accepts the request, it shall assign a unique short address for the device and include it in the association response command.

If the device does not receive the association response command after TBDms it sent the association request command, it shall resend the request. The maximal retry times is 4.

#### Disassociation

The disassociation procedure is initiated by the next higher layer by issuing the MLME-DISASSOCIATE.request primitive to the MLME.

When a coordinator wants one of its associated devices to leave the VPAN, the coordinator shall send a disassociation notification command frame to the device. The device shall reply a disassociation response command frame to the coordinator within TBD ms.

If an associated device wants to leave the VPAN, the MLME of the device shall send a disassociation notification command frame to the coordinator. The coordinator shall reply a disassociation response command frame to the device within TBD ms.

After the device disassociated from the VPAN, the coordinator shall release the resources that has been assigned to the device, such as short address, GTS allocations, etc.

### VPAN Maintenance

#### VPAN ID conflict

In some instances a situation could occur in which two VPANs exist in the same operating space with the same VPAN ID. If this conflict happens, the coordinator and its devices shall perform the VPAN ID conflict resolution procedure.

##### VPAN ID conflict detection

The VPAN coordinator shall conclude that a VPAN ID conflict is present if either of the following applies:

* A beacon frame is received by the VPAN coordinator with the VPAN coordinator subfield set to one and the VPAN ID equal to macVPANId
* A VPAN ID conflict notification command is received by the VPAN coordinator from an associated device on its VPAN.

A device that is associated through the VPAN coordinator shall conclude that a VPAN ID conflict is present if the following applies;

A beacon frame is received by the device with the VPAN coordinator subfield set to one, the VPAN ID equal to macVPANId, and an address that is equal to neither macCoordShortAddress nor macCoordExtendedAddress.

##### VPAN ID conflict resolution

On the detection of a VPAN ID conflict by a device, it shall generate the VPAN ID conflict notification command and send it to its coordinator. The coordinator shall confirm its receipt by sending an ACK frame. Once the device has received the ACK frame from the coordinator, the MLME shall issue an MLME-SYNC-LOSS.indication primitive with the LossReason parameter set to VPAN\_ID\_CONFLICT. If the device does not receive an ACK frame, the MLME shall not inform the next higher layer of the VPAN ID conflict.

On reception of the VPAN ID conflict notification command by the coordinator, the coordinator is notified of the VPAN ID conflict and the MLME shall issue an MLME-SYNC-LOSS.indication to its next higher layer with the LossReason parameter set to VPAN\_ID\_CONFLICT.

On receipt of the MLME-SYNC-LOSS.indication primitive with the LossReason parameter set to VPAN\_ID\_CONFLICT by the next higher layer of the coordinator, it shall first perform a scan and then select a new VPAN ID based on the result of the scan and provide the new VPAN ID to the MLME by issuing a MLME-START.request primitive with the CoordRealignment parameter set to TRUE. The MLME shall perform a VPAN realignment on receipt of the MLME-START.request primitive with the CoordRealignment parameter set to TRUE.

#### VPAN realignment

For the coordinator, it shall generate a coordinator realignment command on receipt of a MLME-START.request primitive with the CoordRealignment parameter set to TRUE. The coordinator shall broadcast the coordinator realignment command containing the new parameters. When a device receives the coordinator realignment command, the MLME of the device shall notify its next higher layer the VPAN realignment by issuing a MLME-SYNC-LOSS.indication primitive.

The coordinator realignment command shall indicate in which superframe the new parameters to be in effect by setting a proper value to the CountDown field in the beacon frame. Both the coordinator and devices shall make sure the new parameters are properly set at the starting point of the effective superframe. The coordinator and the devices shall set the new parameters by issuing a MLME-SET.request primitive to the MLME from the next higher layer.

### Bandwidth allocation and management

A GTS allows a device to operate on the channel within a portion of the superframe that is dedicated (on the VPAN) exclusively to that device. A GTS shall be allocated only by the coordinator, and it shall be used only for communications between the coordinator and a device associated with the VPAN through the coordinator. A single GTS may extend over one or more superframe slots. The coordinator may allocate a number of GTSs at the same time, provided there is sufficient capacity in the superframe.

One or more flows can be setup between the coordinator and a device, the flows can be downlink and uplink. The allocated GTSs for a flow should meet the QoS constraints specified in the TSpec. The way in which the coordinator manages the available resources and the particular schedules it generates are out the scope of this standard. The scheduling is distributed by the coordinator in the beacon frame.

The TSpec describes the set of parameters that define the characteristics and QoS expectations of a particular flow. The format of the TSpec is to be further detailed.

#### Flow establishment

A flow can be originated by the coordinator or a device. The originator shall send a flow establishment request command to the recipient to establish a flow. The recipient shall reply a flow establishment response command to the originator to notify if it accepts the flow establishment request. Both the coordinator and a device can originate a bidirectional flow, in this case, the TSpec of the reverse flow shall be included in the flow establishment response command.

When a coordinator originates a flow, it shall reserve sufficient resources for the flow before it sends the flow establishment request to the recipient device. When a coordinator receives a flow establishment request from a device, it shall first check if there is sufficient resources to meet the QoS requirements, and it accepts the request, it shall reserve sufficient resources for the flow and assign a GTS for this flow. If the coordinator denies the request from a device means that no QoS guarantees can be given, the medium access may still be performed on a priority-basis in the CAP.

The coordinator shall assign a unique Flow\_ID for each flow in the VPAN. In case of the birdirectional flow, the coordinator shall assign different Flow\_IDs for the forward and reverse flows respectively.



Figure 5‑3 Message sequence chart for establish a flow

#### Flow maintenance

The coordinator can monitor the status of the link between a device and itself through the CSI feedback mechanism, and adjust the GTS allocations for the associated flows.

The coordinator may choose to offer a change in the flow parameters by sending a flow modify request command to the device if it decides that the TSpec of the current flow cannot be supported. The device can transmit a flow modify response command to the coordinator indicating whether the offered flow parameters can be accepted or not.

If the coordinator changes the GTS allocation for a flow, the new allocation for the flow will be conveyed in the following beacons.

#### Flow release

If the originator of a flow decides that the flow is required to be released, it shall send a flow release request to the recipient. The recipient shall reply a flow release response command to the originator. The coordinator shall then stop assigning the GTS allocations for the flow.

Figure 5‑4 Message sequence chart for release a flow

### Acknowledgement and retransmission

Both Transmissions with acknowledgement or without acknowledgement should be supported. The next higher layer shall provide the indication whether acknowledgement is required or not when issuing the MCPS-DATA.request primitive to the MAC sublayer. All MAC command frame shall be transmitted with acknowledgement. All broadcast frames, e.g., beacons, shall be transmitted without acknowledgement.

When ACK is not required, the transmission is always assumed to be successful.

If ACK frame is not received or an ACK frame is received with an error when ACK is required, then the device shall conclude the transmission has failed and retransmission is needed.

### CSI feedback and link adaptation

#### CSI feedback for MCS selection

In MAC header, a link adaptation control field is defined.

Table 5‑1 Link adaptation control field

|  |  |  |  |
| --- | --- | --- | --- |
| MCS request | MCS sequence index | Feedback sequence index | MCS feedback |
| 1 bit | [3] bit | [3] bit | [3] bit |
| 0: no MCS request; 1: MCS request | The index of the MCS request. | To which MCS request the MCS feedback applies | Suggest MCS level |

Two types of CSI feedbacks are supported.

* Solicited feedback: a CSI requester request a CSI responder to feedback CSI.
* Unsolicited feedback: a coordinator/device report CSI to another device/coordinator without a request.

For solicited feedback, the CSI requester may set the MCS request to 1 to request a responder to provide MCS recommendation. In each MCS request, the requester shall set the MSI (MCS sequence index) subfield in the link adaptation control field to a value in the range 0 to 6. How the requester chooses the MSI value is implementation dependent.

On receipt of a frame with the MCS request subfield equal to 1, an CSI responder initiates computation of the MCS estimate and labels the result of this computation with the MSI value. The MFB responder includes the received MSI value in the feedback sequence index field of the corresponding response frame. The suggested MCS level is transmitted in MCS feedback field.

For unsolicited feedback, a device/coordinator feedbacks a suggest MCS level without being requested. In this case, feedback sequence index is set to 7, and suggested MCS level is transmitted in MCS feedback field.

After CSI feedback is obtained by the transmitter, it selects a MCS level for future transmissions. The selected MCS level may or may not be the one suggested by the receiver.

The selected MCS level for data transmission is indicated in PHY header.

#### CSI feedback for bit-loading

FFS

#### CSI feedback for MIMO operation

FFS

### Interference coordination

Interference coordination is considered mainly for coordinated topology.

### Mobility and handover

FFS

## Relaying

## Coordinated network

### Channel access

See clause 5.4.1.

### VPAN establishment

Establishing a new VPAN shall start with resetting the MAC sublayer and the PHY layer. The next higher layer of the prospective coordinator shall isuss a MLME-RESET.request primitive to its MLME. The MLME turn off the transceiver by issuing a PLME-SET-TRX-STATE.request to the PHY layer, and then the MAC sublayer is set to its initial conditions, clearing all internal variables to their default values.

The MLME of the prospective coordinator shall respond with a MLME-RESET.confirm primitive to notify the next higher layer the result of the reset operation.

After the reset, the next higher layer of the prospective coordinator shall issue a MLME-SCAN.request primitive to require the MLME to perform a scan to discover other VPANs by obtaining their corresponding beacon frames. The MLME shall perform the scan and report the result of the scan to its next higher layer with a MLME-SCAN.confirm primitive.

After the scan, the next higher layer shall choose a VPAN ID for the new VPAN. The next higher layer provide the new VPAN ID along with other parameters to the MLME by issuing a MLME-START.request primitive. On receipt of MLME-START.request primitive, the MLME shall begin to send beacon frames and operate as a coordinator and the VPAN is established.

### Association and disassociation

#### Association

A device shall perform a passive scan procedure (see clause 5.4.2.1) after it is powered on.

A device may fail to detect any beacon since it locates in the overlapped coverage of different VPANs. If there is no VPAN is detected, the next higher layer may request the MLME to send a beacon request command. After sending the beacon request command, the device shall continue to scan the channel to discover beacon frames or additional beacon frames during Tcoordscan.

A coordinator receives such beacon request commands from a device shall allocate a GTS in the CFP to transmit an additional beacon frame as soon as possible. The additional beacon frame shall be the same as the beacon sent in the BP in the same superframe. The BeaconType field in the beacon frame can be used to identify the type of the beacons. If the coordinator does not receive any association request within TBD ms, it may stop transmit the additional beacons.

The results of the channel scan would have then been used for choosing a suitable VPAN. The algorithm for selecting a suitable VPAN with which to associate from the list of VPAN descriptors returned from the channel scan procedure is out of the scope of this standard.

Following the selection of a VPAN with which to associate, the next higher layers shall request through the MLME-ASSOCIATE.request primitive that the MLME configures the PHY and MAC PIB attributes to the values necessary for association.

The MAC sub-layer of an unassociated device shall initiate the association procedure by sending an association request command to the coordinator of an existing VPAN.

Upon the reception of the association request command, the coordinator shall determine if it will accept the association request and reply an association response command to the device within TBD ms. The coordinator shall indicate if it accepts the request in the association response command, and if it denies the request, it shall also indicate the reason. If the coordinator accepts the request, it shall assign a unique short address for the device and include it in the association response command.

If the device does not receive the association response command after TBD ms it sent the association request command, it shall resend the request. The maximal retry times is 4.

#### Disassociation

The disassociation procedure is initiated by the next higher layer by issuing the MLME-DISASSOCIATE.request primitive to the MLME.

When a coordinator wants one of its associated devices to leave the VPAN, the coordinator shall send a disassociation notification command frame to the device. The device shall reply a disassociation response command frame to the coordinator within TBD ms.

If an associated device wants to leave the VPAN, the MLME of the device shall send a disassociation notification command frame to the coordinator. The coordinator shall reply a disassociation response command frame to the device within TBD ms.

After the device disassociated from the VPAN, the coordinator shall release the resources that has been assigned to the device, such as short address, GTS allocations, etc.

### VPAN Maintenance

#### VPAN ID conflict

In some instances a situation could occur in which two VPANs exist in the same operating space with the same VPAN ID. If this conflict happens, the coordinator and its devices shall perform the VPAN ID conflict resolution procedure.

##### VPAN ID conflict detection

A VPAN ID conflict shall be detected as specified in clause 5.4.4.1.1

##### Resolution

A VPAN ID conflict shall be resolved as specified in clause 5.4.4.1.2.

#### VPAN realignment

VPAN realignment shall be performed as specified in clause 5.4.4.2.

### Bandwidth allocation and management

See clause 5.4.5.

### Acknowledgement and retransmission

See clause 5.4.6.

### CSI feedback and link adaptation

#### CSI feedback for MCS selection

In MAC header, a link adaptation control field is defined.

Table 5‑2 Link adaptation control field

|  |  |  |  |
| --- | --- | --- | --- |
| MCS request | MCS sequence index | Feedback sequence index | MCS feedback |
| 1 bit | [3] bit | [3] bit | [3] bit |
| 0: no MCS request; 1: MCS request | The index of the MCS request. | To which MCS request the MCS feedback applies | Suggest MCS level |

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* Unsolicited feedback: a coordinator/device report CSI to another device/coordinator without a request.

For solicited feedback, the CSI requester may set the MCS request to 1 to request a responder to provide MCS recommendation. In each MCS request, the requester shall set the MSI (MCS sequence index) subfield in the link adaptation control field to a value in the range 0 to 6. How the requester chooses the MSI value is implementation dependent.

On receipt of a frame with the MCS request subfield equal to 1, an CSI responder initiates computation of the MCS estimate and labels the result of this computation with the MSI value. The MFB responder includes the received MSI value in the feedback sequence index field of the corresponding response frame. The suggested MCS level is transmitted in MCS feedback field.

For unsolicited feedback, a device/coordinator feedbacks a suggest MCS level without being requested. In this case, feedback sequence index is set to 7, and suggested MCS level is transmitted in MCS feedback field.

After CSI feedback is obtained by the transmitter, it selects a MCS level for future transmissions. The selected MCS level may or may not be the one suggested by the receiver.

The selected MCS level for data transmission is indicated in PHY header.

#### CSI feedback for bit-loading

FFS

#### CSI feedback for MIMO operation

FFS

### Interference coordination

#### General description

The VPANs managed by the same global controller (GC) forms a VPAN cluster. In this clause, only the intra-cluster interference coordination are specified. At the beginning of the VPAN establishment, the boundary of the superframe of all the VPANs in the same cluster should be aligned.

A device and the coordinator should be capable of detecting the presence of other neighboring VPANs that have the overlapped coverage with the VPAN it associated with. The coordinator is responsible for collecting the interference information from all devices associated with it and report to the global controller. The coordinator should be capable of receive the resource coordination information from the global controller, which will be used for scheduling the allocations in the superframe.

The interference coordination is executed based on the coordination period. The interference information that is reported in current coordination period should be used for the resource coordination during next coordination period. The duration of a coordination period Tcoordination shall equal to the length of TBD superframe.

The interference coordination procedure includes the following mechanisms.

* Interference measurement and report
* Resource Coordination
* Interference parameters/resource coordination update

#### Interference measurement and report

Both a device and the coordinator can detect and measure the interference. The measurement is based on the detection of beacons or reference signals. When a device suffering from interference from neighboring VPANs detects that the interference level excess the predefined threshold, and it does not decide to initiate a handover to a neighboring coordinator, it shall report the detected interference to the coordinator by sending an interference report command. The criteria for a device to decide whether the handover should be performed refers to clause 5.6.9. The coordinator gathers the interference information and reports to the global controller every TBD superframes (i.e., a coordination period).

#### Resources coordination

The global controller allocates resources for the VPANs that it manages and notify the coordinators about the allocations. The coordinator that does not receive the allocations information from the global controller can makes the scheduling by itself; the coordinator that receive the allocations information from the network controller shall take the allocation information into account while makes the scheduling. The rules and criteria for resource coordination is out of the scope of this standard.

#### Interference coordination update

Both the device and the coordinator shall be capable of updating the interference information.

When a device suffering from interference from neighboring VPANs that has reported the interference information to the coordinator detects the change of parameters related to the interference, it shall update the parameters related to the measured interference to the coordinator by sending an interference The coordinator gathers the updated interference information and reports to the network controller along with new interference information every coordination period.

If a device that is suffering from interference from neighboring VPAN and is involved in the coordination disassociates with the VPAN, the coordinator shall be able to learn the leave of that device as soon as possible and report this to the global controller in next report event.

Figure 5‑5 An example of the interference coordination

### Mobility and handover

Two scenarios are considered. First is LIFI only scenario, therefore handover is made between VLC VPAN and VLC VPAN. Second is LIFI + WIFI heterogeneous network.

#### Scenario 1: LIFI only

Two types of handover are supported,

* Type1, over the air: handover is initiated by device
* Type2, over the backhaul, handover is initiated by controller

##### Type 1 handover: over the air

After association to a serving coordinator, a device may scan the area for available neighboring coordinators and perform received signal strength (RSS) measurement. The measurement is based on beacons or reference signals.

A device may perform alpha-filtering on the measurements based on

Where is the latest received measurement result from the physical layer; is the updated filtered measurement result, that is used for evaluation of reporting criteria or for measurement reporting; is the old filtered measurement result; is a filtering-coefficient that can be configured.

If the RSS of neighbor cells satisfy

Then the device should initiate the handover to the target coordinator. Here is the RSS of the target coordinator and is the RSS of the associated coordinator and is a predefined threshold.

Once the handover is initiated by the device, it sends a re-association request to the target coordinator. The device uses the re-association request to request association as well as to send its preferred QoS requirements to the target coordinator.

In the association response message, the target coordinator indicates whether the request is permitted. Besides, the target coordinator also inform the QoS resources allocated to the device, or suggests alternate level of QoS the target coordinator can support.

The previous coordinator may continue to send the packets that have been store in the buffer to the device. The device may receive these packets to its best effort. If the previous coordinator does not received acknowledgement from the device for N consecutive frames, then the previous coordinator consider the device has left the VPAN and the transmission is ceased.



Figure 5‑6 type 1 handover: over the air

##### Type 2 handover: over the backhaul

After association to a serving coordinator, a device may scan the area for available neighboring coordinators and perform received signal strength (RSS) measurement. The measurement is based on beacons or reference signals.

A device may perform alpha-filtering on the measurements based on

Where is the latest received measurement result from the physical layer; is the updated filtered measurement result, that is used for evaluation of reporting criteria or for measurement reporting; is the old filtered measurement result; is a filtering-coefficient that can be configured.

If the RSS of neighbor cells satisfy

Then the device should send RSS measurement report to the associated coordinator periodically. Here is the RSS of the target coordinator and is the RSS of the associated coordinator and is a predefined threshold.

The coordinator can send the measurement report to the global controller together with the QoS requirement of the device.

If the global controller decides to handover the device to the target coordinator, it sends its decision to the current coordinator. It also notify the target coordinator about the upcoming handover together with QoS requirement.

Current coordinator send handover command frame to the device.

Then the device send re-association request to the target device.

In the association response message, the target coordinator confirms the handover. Besides, the target coordinator also inform the QoS resources allocated to the device, or suggests alternate level of QoS the target coordinator can support.



Figure 5‑7 Type 2 handover: over the backhaul

#### Scenario 2: LIFI + WIFI



Figure 5‑8 Handover for heterogeneous RF+VLC network

For heterogeneous operations of LIFI and WIFI, three types of handover are envisioned.

* Type1 handover: WIFI => WIFI + VPAN
* Type2 handover: WIFI + VPAN => WIFI
* Type3 handover: WIFI + VPAN1 => WIFI + VPAN2

##### Type1 handover: WIFI => WIFI + VPAN

Similar to association procedure, the device can send an association request to a target coordinator is the RSS meet the requirement.

##### Type2 handover: WIFI + VPAN => WIFI

After associating to a serving coordinator, a device may scan the area for available neighboring coordinators and perform received signal strength (RSS) measurement. The measurement is based on beacons or reference signals.

A device may perform alpha-filtering on the measurements based on

Where is the latest received measurement result from the physical layer; is the updated filtered measurement result, that is used for evaluation of reporting criteria or for measurement reporting; is the old filtered measurement result; is a filtering-coefficient that can be configured.

If no neighbor coordinator with satisfactory RSS can be found and meanwhile the RSS of associated coordinator is falls below a predefined threshold

Then the device should send RSS measurement report to the associated coordinator periodically. Here is the RSS of the associated coordinator and is a predefined threshold.

The coordinator can send the measurement report to the global controller together with the QoS requirement of the device.

If the global controller decides to handover the device to WIFI only, it sends its decision to the current coordinator and steer traffic to the WIFI.

Current coordinator then sends dissociation command frame to the device.

##### Type3 handover: WIFI + VPAN1 => WIFI + VPAN2

Same as scenario 1, can be either over-the-air or over-the-backhaul.

## Heterogeneous Operation of different OWC PHY modes

## MAC frame formats

The MAC frame format is composed of a MHR, a MSDU and a MFR. The specific fields of each component is for further study.

## Command frames

## Primitives for data service

Primitives for management service

# MAC PIB attributes

**Dear Proposer: add any anticipated MAC PIB attributes here**

See table 60 in IEEE802.15.7-2011 for the current MAC PIB Table.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **MAC PIB Table 60 Additions** | | | | | |
| **Attribute** | **Identifier** | **Type** | **Range** | **Description** | **Default** |
|  |  |  |  |  |  |
|  |  |  |  |  |  |
|  |  |  |  |  |  |
|  |  |  |  |  |  |

1. The PHY parameters are derived from the ITU-T recommendation G.9960 (12/2015). They were generically scaled towards lower and higher bandwidths, for achieving improved energy efficiency and higher data rate, respectively. [↑](#footnote-ref-1)
2. Max./Min. data rates assume that all used subcarriers are occupied. Max. rates assume 12 bits/subcarrier and code rate 20/21. Data rate is variable by means of adaptive bitloading, different FEC rates and repetitions. Min. rates assume 1 bit/subcarrier, rate ½ and 3 repetitions. Even lower data rates are possible by partial usage of subcarriers though adaptive bitloading. [↑](#footnote-ref-2)
3. Actually, this is step is left out in the 3GPP LTE specification but needed in the more sophisticated schemes described in following subsections for consistency with classical SC transmission. [↑](#footnote-ref-3)
4. In Matlab, this is the function floor(*z*). [↑](#footnote-ref-4)
5. In G.9963 the same preamble and header are transmitted by both transmitters, then there is one ACE that is also transmitted by both transmitters but the second transmitter inverts the sign. In a 2x2 MIMO link, for instance, only one additional channel estimation symbol is needed that is also transmitted by the other transmitter. [↑](#footnote-ref-5)
6. Channel estimation can be performed by correlation, at the same subcarrier, over multiple OFDM symbols. [↑](#footnote-ref-6)
7. An alternative would be the use of Hadamard sequences. However, imprecise channel estimates were observed experimentally in [13] when using the Hadamard sequence with ones only. [↑](#footnote-ref-7)
8. This is reached by assigning a different comb of subcarriers to each AP that is shifted in the frequency domain by integer multiples of the subcarrier spacing depending on the AP. It is assumed that the receiver is capable to interpolate the channel between the used subcarriers in the comb. [↑](#footnote-ref-8)