**IEEE P802.15**

**Wireless Personal Area Networks**

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| Project | IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs) | |
| Title | **Proposal for TG7r1 High-rate PD Communications** | |
| Date Submitted | [January 10, 2016] | |
| Source | TG7r1 |  |
| Re: |  | |
| Abstract | This document describes a PHY and MAC proposal for High-rate PD communications addressing the requirements in the Technical Considerations Document. | |
| Purpose | Proposal | |
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# Overview

## Scope

This proposal defines PHY and MAC layers for *high rate photodiode communications* in a next-generation optical wireless communications system. This proposal is to support fixed wireless links and multiple mobile user links via an optical wireless infrastructure, which consists of one or more wireless access points. This proposal supports a range of data rates (i.e., 1 Mb/s to 10 Gb/s), targeting the efficient use of the available optical bandwidth under variable channel conditions. This proposal also describes unified interfaces for the user plane and the control plane information, which can be used to optimize the links and to support seamless mobility.

## Purpose

This proposal extends the optical wavelength range beyond the scope of the existing IEEE 802.15.7 standard for visible light communication also below and above the wavelengths of 380 nm and 780 nm, respectively hereby including the invisible light. Moreover, this proposal introduces new transmission modes for higher data rates up to 10 Gb/s, using new wireless transmission technologies, such as orthogonal frequency-division multiplexing, adaptive transmission, multiple-input multiple-output and coordinated networking using multiple access points to provide mobility for multiple mobile users in an optical wireless network infrastructure. Furthermore, this proposal enables the coexistence of optical wireless with radio-based links.

# Normative references

To be done

# Definitions, acronyms and abbreviations

## Definitions

To be done

## Acronyms and Abbreviations

a.k.a. also known as

AP access point

BER bit-error rate

CIR channel impulse response

CO coordinated network topology

C-RAN cloud radio access network

CRS cell-specific reference signal

CSI channel state information

CSK color shift keying

DAC digital-to-analog conversion

DFT discrete Fourier transform

DMT discrete multi-tone

DSP digital signal processor

EVM error vector magnitude

FDMA frequency-division multiple access

FDZP frequency-domain zero-padding

FDE forward error correction

FEC forward error-correction

FFT fast Fourier transform

GMSK Gaussian minimum shift keying

HARQ hybrid automatic repeat request

IDFT inverse discrete Fourier transform

IFFT inverse fast Fourier transform

LED light-emitting diode

LD laser diode

LOS line-of-sight

LPF low-pass filter

MAC medium access control layer

MIMO multiple-input multiple-output

MRC maximum ratio combining

MSK minimum shift keying

NC network controller

NLOS non-line-of-sight

OFDM orthogonal frequency-division multiplexing

OWC optical wireless communication

P2P peer-to-peer topology

PD photodiode

PHY physical layer

RA random access

S star topology

SFO sampling frequency offset

SISO single-input single-output

SINR signal-to-interference-and-noise ratio

SNR signal-to-noise ratio

TDMA time-division multiple access

TTS transmission test symbol

URS user-specific reference signal

VID VLAN identifier

VLAN virtual local area network

VLC visible light communications

UD user devices

WDM wavelength-division multiplex

# General description

## Introduction

This proposal extends the capabilities and improves the transmission performance of optical wireless communications (OWC) in order to address the specific requirements of new use cases in new scenarios[[1]](#footnote-1) mentioned in the Technical Considerations Document (TCD) for 802.15.7r1 [8], such as a wireless access in indoor/home/office, industrial wireless (with specific requirements for robustness, low latency and secure wireless transmission, communications between vehicles and vehicle-to-the-roadside-infrastructure communications, and as a wireless backhaul technology.

## Scope

This proposal supports fixed wireless links and multiple mobile user links via an OWC infrastructure, which consists of one or more wireless access points. This proposal 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 available optical bandwidth under variable channel conditions.

This proposal introduces modern wireless transmission technologies into an OWC standard, such as orthogonal frequency-division multiplexing (OFDM), adaptive transmission, multiple-input multiple-output (MIMO) and coordinated networking of multiple access points (APs) to provide mobility for mobile user devices (UDs) in a 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).

Unified interfaces are introduced for the user plane as well as open interfaces to the control plane information, which can be used at the network layer to optimize the links and to support user mobility. These interfaces enable also the coexistence of OWC with radio based wireless links.

## Network Architecture

### Introduction

I order to address the variety of use cases, a bottom-up approach is followed that develops the required network topologies with increasing degree of sophistication.

### Network topologies

|  |
| --- |
| Figure - Topology of peer-to-peer (P2P), star and coordinated network |

In addition to the peer-to-peer (P2P) and star (S) topologies described in 802.15.7, this proposal supports an additional coordinated network (CO) topology, enabling mobility among multiple access points (APs), i.e. handover and interference coordination. These topologies are shown in Figure 1. The broadcast topology, where the downlink is used only, from one or multiple APs to one or multiple user devices (UDs), is also supported but not explicitly shown in Figure 1.

This proposal defines all methods at the PHY and MAC layers for operating the link in P2P, S and CO topologies. The proposal will be described bottom-up, starting with the SA topology and subsequently including the functionality required for S and CO topologies.

Note that the coordination in the S and CO topology is not part of this proposal. Rather, the wireless links are defined, including the required reference signals as well as feedback and control channels between UDs, APs and the NC, which are needed to support the above functionality.

#### Peer-to-peer

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 for all topologies, the MAC layer supports an automatic link setup and a feedback path required for closed-loop link adaptation. No NC and AP functionality are required in the P2P topology.

#### 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 link requires additional functionalities. One UD acts as AP serving multiple other UDs in parallel and coordinating their wireless transmission. PHY and MAC support spectrally efficient transmission. Network access is contention-based, with appropriate resolution. The feedback from UDs is transmitted in an orthogonal manner, i.e., contention-free. An additional control channel is broadcast to all UDs in order to inform them about the granted transmission resources time slot in TDMA mode and frequency sub-band in FDMA mode for both link directions. Dynamic bandwidths sharing among multiple UDs is supported in a contention-free manner in both directions.

#### Coordinated network

In the CO topology, multiple UDs are served by multiple APs, which are in turn coordinated by a network controller (NC). The NC reroutes the traffic paths between NC and APs in case of handover and controls the transmission of all APs and UDs to minimize the interference. Therefore, all APs are time-synchronized, e.g. by using the IEEE 1588 precision time protocol (PTP). The NC also aggregates the wireless traffic of all UDs and APs.

UDs and APs estimate the physical interference channel before CO transmission. The respective metrics reports are conveyed by the APs over the fronthaul to the NC where it is needed for interference coordination and handover. By additionally knowing the interference conditions, transmissions can be optimized, as interference is avoided and can even become a useful signal.

### Essential Features

#### Use cases

This proposal supports use cases B1-B4 and all light sources described in the TCD [8].

#### Transfer mode

This proposal supports bidirectional, continuous and packet-based OWC.

#### Data rates

This proposal supports variable data rates from 1 Mbit/s to 10 Gbit/s, depending on the use case.

A transceiver with a small bandwidth can synchronize with respect to, and exchange control information and data with another transceiver having a higher bandwidth, and vice versa. Therefore, links are operated at low bandwidth during link setup, and bandwidth is increased if possible.

#### Waveform

An adaptive OFDM waveform with optional precoding is used. The used bandwidth is scalable by means of a variable number of subcarriers while keeping the same carrier spacing and cyclic prefix (CP) in all bandwidths modes. Devices with different bandwidth are interoperable. 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 OWC link.

#### Efficient use of the optical bandwidth

This proposal supports the efficient use of the optical bandwidth by means of closed-loop adaptive transmission and MIMO. This allows robustness in the multi-path propagation channel. Moreover, PHY and MAC layer are defined so that latencies less than 1 ms are achievable.

#### Dimming support, coexistence

This proposal 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

This proposal defines the metrics to be reported by the PHY and MAC and makes those reports available to higher layer protocols. Reporting includes signal strength of strongest APs and UDs, signal-to-interference-and-noise ratio (SINR) vs. frequency and channel state information (CSI) for strongest APs and UDs. Short time intervals between metric reports and control messages ensure fast adaptation to the time-varying wireless channel as well as low latency.

#### Advanced wireless networking, high availaility

This proposal allows robust transmission for all channel conditions. Advanced wireless networking is supported in S and CO topologies. The link is available in line-of-sight (LOS) and also in non-LOS (NLOS) scenarios, at low signal-to-noise ratio (SNR) and in interference-limited scenarios.

# MAC

### Duplex Mode

Full and half duplex are both supported. Half duplex can be combined with same wavelength or different wavelengths in both directions. In half duplex, time sharing can be unequal for both link directions, so that statistical multiplexing gains and higher peak rates in each direction are possible. Full duplex is typically combined with different wavelengths in uplink and downlink (e.g. visible light in the downstream, infrared in the upstream). Same wavelength can be used in the directive backhaul scenario B4. But even in B4, full duplex is costly from implementation point of view, as RF crosstalk must be avoided.

### Superframe

A super-frame (SF) is introduced in general. In the peer-to-peer (P2P) mode, UDs can access the channel randomly, i.e. contention-based. In the star mode, UDs can access the channel either contention-based, or be assigned individual time slots (time-division multiple access, TDMA) and/or individual frequency sub-bands (frequency-division multiple FDMA). In a MIMO link, multiple UDs can be assigned the same time-frequency resource while data are delivered on different spatial sub- streams, what is a.k.a. as space-division multiple access (SDMA). In the relaying mode, an OWC link can be established over multiple hops. In the coordinated network, adjacent APs with overlapping coverage are mutually coordinated to optimize the performance.

### SF for P2P

### SF for Star

### SF for Relaying

### SF for Coordinated network

### Peer-to-peer

The P2P mode is a standalone link between two UDs. It is used in ad-hoc situations if no device with AP functionality is available. As multiple P2P links can coexist in the same area, like in cf. vehicle-to-vehicle communications, interference coordination is taken into account

### VPAN establishment

At the beginning of the super-frame, if no AP is available, the UD sends a short beacon frame which contains only the preamble and the header. The beacon allows the UDs to identify another UD and to learn its physical properties (number of LEDs, colors, Ethernet MAC and IP addresses, local time at the UD etc.).

### Association and disassociation

In P2P mode, UDs access the channel randomly, i.e. contention-based (at time offset 0, see below). UDs listen before they talk. The first UD sends a short random access (RA) frame that contains only the preamble and a header. The RA frame allows another UD to identify the first UD, to learn its physical properties (number of LEDs and colors, Ethernet MAC and IP addresses etc.) as well as the properties of the transmission channel.

In case that transmission is completed, in order to save energy, a UD can send another short RA frame after a certain period of time, in order to inform the other UD that it is going to idle mode. In that case the transmitter is switched off, and the receiver goes to the lowest bandwidth mode, see Section 5.7.

### Link maintainance

To be further detailed.

### CSI feedback and link adaptation

CSI feedback is provided only if a UD detects a significant change of the channel state which implies a desirable change of the transmission mode.

Using CSI feedback, the source UD is informed about a transmission mode that can be decoded by the destination UD reliably. CSI feedback can be provided in both link directions.

CSI feedback is provided randomly in the last time slot in a superframe, using listen before talk.

The PHY measures the signal-to-interference-and-noise ratio (SINR) on each subcarrier. The method itself is proprietary. It is in the responsibility of the implementer to provide reasonable CQI reports and to ensure that the data delivered in the requested modulation and coding scheme can be received with negligible probability of error. The transmitter will reduce the rate in general if there are too many packets reported with errors.

A common approach to estimate the SINR is to pass the reference symbols provided for channel estimation also through the frequency-domain (and eventually MIMO) equalizer. Per stream, the deviation of the received constellation from the transmitted one being known also at the receiver is then measured per subcarrier. The deviation is normalized so that the error vector magnitude (EVM) can be measured.

where is the received complex-valued signal constellation and the desired one. However, this is a snapshot only and averaging may be required. In case that the subsequent data block is received free of error, i.e. the cyclic redundancy check (CRC) has been passed, one way is to re-encode the data and pass them through the constellation mapper, so that more reference points can be obtained. There is an inverse relationship between the SINR and EVM

The procedure used here is feasible only if reference signals are provided on each subcarrier. A more sophisticated SINR estimation method is needed in the CO mode.

Quantization of the SINR in steps of 1 dB yields the channel quality indicator (CQI). The CQI is an integer number, ranging e.g. from 0 to 63 using 6 bits, where values below 0 dB are set to 0 to indicate that no transmission is possible on this particular subcarrier

The PHY creates an ordered list containing the CQIs for all subcarriers. The list is extracted from the PHY and transported over the reverse link as a data block in a normal PHY frame. A separate CQI list is reported for each parallel stream in an optical MIMO or WDM link.

For reliable transmission of feedback packets, a robust modulation scheme is used. Feedback packets are transported with reduced bandwidth, in the 10 MHz mode in Table 1, thus by using the lowest SCs, as this is not otherwise negotiated between the transmitter and receiver.

#### Interference coordination

In case that a collision is detected, the first UD stops RA frame transmission and retransmits the RA frame at another time offset. The time offset for RA frame transmission is measured in the local time at the UD, which is regularly synchronized with the AP by using the preamble. The time offset *Toffset = O*of the RA frame is an integer multiple denoted by *O* of a constant offset denoted by **To be further detailed.

#### Acknowledgement and retransmission

Error detection is an integral part of the complex, soft-decision LDPC decoder. If an erroneous packet is received, via the reverse link, the transmitter can be asked by the receiver to retransmit this packet. Selective Repeat (SR) is known as an efficient implementation of automatic repeat request (ARQ). In order to reduce latency, SR is implemented in front of and after the FEC at the transmitter and receiver, accordingly.

For SR, buffering of already transmitted data in the MAC is done at the transmitter. In case of an erroneous packet, the receiver retransmits short negative acknowledgement (NACK) fame, containing only the preamble and the header with the NACK message and the number of the packet to be retransmitted. Retransmission of the packet is implemented immediately, i.e. SR packets are prioritized with respect to other data. The reordering of packets is implemented so that the delay of packet delivery to higher layers is minimized.

To be further detailed.

### Star

In the star topology, transmission is coordinated by an AP. UDs access the channel randomly, i.e. contention-based, or transmission is coordinated using time-division multiple access (TDMA), frequency-division multiple access (FDMA) and space-division multiple access (SDMA).

### VPAN establishment

The first time slot in the super-frame is reserved for contention-based multiple access (CBMA). In this slot, the AP sends a short beacon frame at first containing only the preamble and a header. The beacon frame allows the UDs to identify the AP and to learn its physical properties (number of LEDs and colors, Ethernet MAC and IP addresses, local time at the AP etc.).

### Association and disassociation

Subsequently, UDs can access the channel randomly (at time offset 0, see below) and inform the AP that they want to access the network. Using CBMA, UDs listen before they talk. The UD sends a short random access (RA) frame which contains only the preamble and a header which allows the AP to identify the UD and to learn its physical properties (number of LEDs and colors, Ethernet MAC and IP addresses etc.).

In case that a collision between multiple UDs is detected, a UD stops its RA frame transmission and retransmits the RA frame at another time offset. The time offset for the RA frame transmission is measured in the local time at the UD, which is regularly synchronized with the AP by using the preamble. The time offset *Toffset = O*of the RA frame is an integer multiple denoted by *O* of a constant offset denoted by **To be further detailed.

In case that transmission is completed, in order to save energy, a UD can send another short RA frame after a certain period of time, in order to inform the AP that it is going to idle mode. In that case the transmitter is switched off, and the receiver goes to the lowest bandwidth mode, see Section 5.7.

### Link maintainance

To be further detailed.

### CSI feedback and link adaptation

CSI feedback is provided only if the AP or UD detect a significant change of the channel state which implies a desirable change of the transmission mode.

Using CSI feedback in the downlink, the AP is informed about a transmission mode that can be decoded by the UD reliably. In case that the UD requests a time slot for uplink transmission, the CSI feedback is also provided from the AP to the UD.

For CBMA, CSI feedback is provided randomly in the last time slot in a superframe, using listen before talk.

For TDMA, FDMA and SDMA, in the last time slot of a super-frame, the AP informs all associated UDs at first about the order of CSI feedback transmission, being identical to the order of data transmission in the next superframe.

After being informed about the order of feedback transmission, UDs reply with their individual CSI feedback transmission to the AP in the assigned order.

As a specific feature of FDMA and SDMA, a so-called resource map (RM) is broadcast from the AP to all UDs as a data packet in a specific control frame. This packet informs the UDs per time slot, per spatial stream and per frequency subband (if applicable) what the destination UD in the downlink is and what modulation and coding scheme is being used (downlink RM). Moreover, this packet informs the UDs per time slot, per spatial stream in the uplink and per frequency subband (if applicable), what the source UD in the uplink is and what modulation and coding scheme is being used (uplink RM). Sophisticated rules are applied to minimize the control overhead while targeting reliable transmission of the control information.

### Interference coordination

To be further detailed.

### Acknowledgement and retransmission

To be further detailed.

### Ranging and power control

UDs can have different path loss and distance for the AP. Thus, longer CP or ranging are needed.

The random time offset, which is however always on a fixed grid, enables the AP to measure the roundtrip time for each UD. In the last time slot of the superframe, the AP informs all UDs about their transmit power and the number of samples by which their transmission shall be individually delayed, so that the signals arrive nearly simultaneously and the mutual delays between UD signals is much smaller than the CP duration.

To be further detailed.

### Mobility and handover

To be further detailed.

### Relaying

### Coordinated network

### VPAN establishment

To be further detailed.

### Association and disassociation

To be further detailed.

### Link maintainance

To be further detailed

### Association and disassociation

To be further detailed.

### CSI feedback and link adaptation

In CO mode, a feedback packet contains additional information, over what path in the network this information is conveyed, and to what other device. This is indicated by an IP address, or an Ethernet MAC address plus a virtual local area network (VLAN) identifier (VID).

in the absence of interference. The SINRn on each subcarrier is measured in dB and obtained as[[2]](#footnote-2)

To be further detailed

### Acknowledgement and retransmission

To be further detailed.

### Ranging and power control

To be further detailed.

### Mobility and handover

To be further detailed.

### Heterogeneous operation of different OWC PHY modes

In NLOS scenarios, or if the LOS signal is weak, the path loss is high. The channel is useful only in a limited bandwidth of 10 MHz and sometimes less. Moreover, devices with different bandwidths shall be interoperable. It is intuitive to reduce the used bandwidth with full power.

For data, both requirements can be met by using a consistent numerology together with bit- and power loading. However, preamble and header need to support this same feature. This proposal supports used-bandwidth adaptation for link optimization in poor channel conditions. Adaptation is controlled by the MAC and used-bandwidth information is contained in the header, see Section 6.

The used bandwidth can be reduced in steps and the power redistributed, accordingly. In case of poor channel conditions (i.e. low power and reduced bandwidth), the MAC switches the PHY to a reduced bandwidth mode (e.g. 200 🡪 10 MHz). During the link setup and for control information broadcasts to multiple users, the lowest bandwidth mode is always used.

### Frame formats

(here we can specify different MAC frame formats, such as beacon frame; acknowledgement frame; command frame)

### Command frames

(here we specify the contents of different command frames, such as association request, CSI feedback, scheduling request)

### Primitives for data services

(here we specify the primitives needed to support MAC data services. Such as MCPS-DATA.request, MCPS-DATA.confirm, etc)

### Primitives for management services

(here we specify the primitives needed to support MAC management services. Such as MLME-ASSOCIATE.request, MLME-GTS.request, etc)

# Generic PHY

The physical layer can be operated in various modes using parameter sets defined in the Numerology given in .

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| Figure 2 - Overview of the standalone link (one link direction). |

### Adaptive OFDM concept

An overview of the P2P link is shown in Figure 2. At the transmitter (Tx), the parallel input data streams 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 usually added in the analog domain 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)).

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 mapping of information bits onto the sub-carriers is based on the SINR used as a metrics and reported as feedback over the reverse link direction. In Figure 2, the EVM metrics report is denoted as noise enhancement vector. A power- and bit-loading algorithm determines the power and appropriate modulation formats for the data transport on each used subcarrier. Typically, the loading algorithm maximizes the throughput assuming a certain power budget so that a predefined bit error rate (BER) is achieved before forward error correction (FEC).

### Frame Structure

The data signal is transmitted together with additional signals in a compound frame as shown in Figure 3, which can be decoded frame-wise. The preamble allows coarse synchronization and channel estimation, enabling the Rx to decode the header information. The P2P header contains the control plane information needed to setup the link and to decode the subsequent data packet. Following the header are blocks containing the data. The data block contains additional reference signals that can be used to correct distortion due to the sampling frequency offset between low-cost UDs.

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| Figure – P2P PHY frame. |

### Preamble

The P2P preamble allows coarse synchronization, power estimation and channel estimation so that the header can be correctly decoded. In the P2P mode, the preamble of the coax mode in the G.hn standard is used as baseline, see tables 7-65 and 7-76 in [4].

For optimization in low SNR, further optimization is considered, as proposed in [9] where six consecutive sequences 𝐴*NP/6* with specific sign are used as [𝐴*NP/6*, 𝐴 *NP/6*, −𝐴 *NP/6*, 𝐴 *NP/6*, −𝐴 *NP/6*, −𝐴*NP/6*] where NP denotes the total preamble length excluding the last symbol for channel estimation. This approach yields a sharp peak in the time metric when using the Schmidl-Cox algorithm for detection of the preamble [10]. Optimization target are accurate synchronization and improved robustness against the noise and multipath.

### 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 in the P2P link, and in S and CO topologies, additional OFDM symbols are used for channel estimation. These additional symbols are sent after the header, as part of the data block in the frame.

### Header

P2P header information is generally defined in the MAC layer, see Section 6. Header information is normally transported using OFDM. The same numerology is used like in the last preamble symbol for channel estimation. For optimization at low SNR, pre-coding is proposed, see Section 5.1.5.2. Header information is only transported by the PHY which establishes a transparent link for the control plane. Information in the P2P header is used to setup the link and to decode the data in SISO mode. Moreover, feedback information is transported for closed-loop adaptation.

### Data

Data are transported using the same numerology used in the last symbol of the preamble. The data block contains additional reference signals for correction of the sampling frequency offset (SFO) and may contain additional reference symbols for MIMO. Moreover, the data block may contain more detailed metrics reports and additional control information for the data transport. The MAC informs the receiver about the formatting of the data block.

### Waveform

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

i) The waveform is always non-negative and real-valued.

ii) Clipping if needed is implemented in the digital domain.

iii) Precoding can be used to improve the power efficiency and support dimming.

### Adaptive OFDM signal generation

OFDM signal generation is shown in Figure 4. A block of 2*N* data symbols is transmitted. Following an optional pre-coding to improve power efficiency and support dimming, the signal is 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 - OFDM signal generation |

#### Carrier mapping

Carrier mapping is performed as illustrated in Figure 5. Note that the subcarrier x0 could 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

.

The resulting discrete multi-tone (DMT) signal is real-valued, even if symbols *xn* 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 - Carrier mapping for standalone link |

#### IFFT

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

where *k* denotes the sample index, *xn* 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 Figure 6. 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, so that a simple 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 - Cyclic Prefix insertion |

#### 

#### Single-carrier modulation (optional)

Optional precoding infront of the OFDM modulator can be used to reduce the probability of clipping and enhance power efficiency while sacrificing no or minor spectral efficiency see [2, 3].

For single-carrier (SC) transnmission, “outer” precoding, together with an “inner” OFDM transmitter is used to emulate SC transmitter inside the OFDM concept. These schemes require little more advanced signal processing, and the same minor increase of sophistication can be expected at the receiver, i.e. the decoding is straightforward. The schemes are shown in principle in Figure 5. More details can be found in [2, 3].

#### Pure DFT precoded SC

The well-known SC-FDMA transmitter from 3GPP LTE is shown in Figure 5, row A. First, the symbol sequence is passed through the N-DFT and then mapped directly onto the desired frequency sub-band using a cyclic shift (CS) so that the DC signal is in the center (actually, this is not done in the 3GPP LTE air interface but needed in the next section). 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 with a Nyquist pulse-shape and a roll-off factor of =0. As the this is a special case of the filtered SC transmission, details are described in the next subsection.

#### RRC-filtered SC

In the middle row in Figure 5, an additional root-raised-cosine filter is introduced in the frequency domain where >0. In order to realize filtering, 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 onto then mapped directly onto the desired frequency sub-band using a cyclic shift (CS) so that the DC signal is in the center. the desired center subcarrier.

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

with ,

where *k =* 1, 2*, …, F∙N* and *M* is the number of samples in the final waveform. The notation is used to indicate that *z* is rounded to the nearest integer less than or equal to *z*.[[3]](#footnote-3) Note that F-times up-sampling followed by *M*-DFT is equivalent to *N*-DFT and subsequent spectral repetition, provided that the ratio *M/N* is an integer. The proof is given in [3]. Accordingly, up-sampling and *M*-DFT can be replaced by *N*-DFT and repeating the output signal in the frequency domain. Next, a frequency-domain filter is implemented so flexibly that bandwidth can be changed as a function of the block size *N*. Therefore, a vector is defined with running index s = [-N, …; :::;N]

and compute the bell-shape part of the filter

1. **Minimum-shift keying:** In the bottom row of Figure 5, these two well-known schemes have been extended in order to emulate the Gaussian minimum shift keying (GMSK) which is well known from 2G GSM networks. Instead of the RRC filter, a Gaussian filter is used and a minimum-shift keying modulator (MSK) in the time domain. GMSK yields a waveform with a constant envelope.

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| Figure - Different precoding schemes can be used to improve the power efficiency of the OFDM transmitter. Top: Pure DFT precoding emulates a Nyquist pulse with roll-off factor =0, as introduced in 3GPP LTE Rel. 8. 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.    More to be taken over from [3]. |

#### Unipolar modulation (optional)

to be further defined.

### MIMO

#### Modified frame structure

The use of multiple-input multiple-output (MIMO), wavelength-division multiplexing (WDM) and wavelength-shift keying (WSK) causes a change of the frame structure. Preamble and header remain unchanged. Initial link setup and header detection are performed in the SISO mode. Detection can be improved by transmitting the same signal from all LEDs, and maximum ratio combining (MRC). The number of LEDs is available in the header. However, there are additional MIMO reference symbols (RS) sent at the beginning of the data block, see Figure 8. MIMO RS have the same numerology as used for data.

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| Figure – Additional MIMO reference symbols are used at the beginning of the data block. |

#### Reference symbols for MIMO channel estimation

MIMO RS for channel estimation are defined in the frequency domain and over multiple OFDM symbols. For MIMO, the same reference symbol is always used by all LEDs, but multiplied as a whole with another sign taken out of an orthogonal sequence. This approach is more power efficient and provides a reduced error vector magnitude of all channel estimates.

Channel estimation can be performed by correlation, at the same subcarrier, over multiple OFDM symbols, as in IEEE 802.11n. For 1-4 LEDs, the MIMO reference signals are given by[[4]](#footnote-4)

* 1 LED: [{sn}]
* 2 LEDs: 1st LED [{sn} {sn}], 2nd LED [{sn} {-sn}].
* 4 LEDs: 1st LED [{sn} {-sn} {sn} {sn}], 2nd LED [{sn} {sn} {-sn} {sn}],

3rd LED [{sn} {sn} {sn} {-sn}] , 4th LED [{-sn} {sn} {sn} {sn}].

LEDs occupy a wide optical spectrum. Note that channel estimation for interference suppression in color shift keying (CSK) and wavelength-division multiplex (WDM) can be supported with the same concept used for MIMO. For each LED color, different MIMO reference signal is used. If the spectral overlap of LEDs with different colors is negligible, the same sequence can be reused for several wavelengths. The assignment of colors to sequences is included in the header.

#### MIMO transmission modes

In this chapter, several transmission modes will be described how an OWC MIMO link can be operated. The main objective here is to enable a dynamic tradeoff between spatial diversiy and spatial multiplexing, so that the optimal number of streams is always selected to maximize throughput and to operate the link reliably. It is assumed that the MIMO link will be operated adaptively in a closed-loop manner based on metrics reporting described in section 5.1.9.5.

#### 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 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, and 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 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 verctor **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 then boosted differently, according to the singular value corresponding to each stream at the given sub-carrier index.

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 the noise variance at one receiver, respectively.

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| Figure – Adaptive MIMO transmission system. |

#### 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 data streams is used because in some cases, depending on the time-variant mobile channel, a higher capacity is reached with a reduced number of sub-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 shtreams, where Q can be any integer ranging from 1 to *nTx* where *nTx* denotes the total number of transmitters. This configuration is introduced. The data in each stream are transported using an individually selectable modulation scheme, 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 cannot vary only over time, but also as a function of the modulation frequency. 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 in order to reduce complexity.

1. **Spatial repetition code:** One important simplification is that only one stream is transmitted over all LEDs. This mode is useful, e.g., in order to create an omni-directional characteristics. This is reached using the precoding vector **v**n = (1 1 1 1 …1)T. 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.
2. **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 single ADC and IFFT are sufficient.
3. **Combinations for multiple streams:** There can be a combination of the above two schemes applied for each stream individually. At the receiver side, the residual cross-talk can be reduced by multi-stream processing.
4. **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.
5. **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.

### Channel coding

#### 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.

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| Figure 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]. For initial performance evaluation, an LDPC code with information block size of 4320 bits and a code rate of 5/6 has been used. Other block sizes and code rates are of course possible and their use is for further study.

#### 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.

### Relaying

#### Modified frame structure

#### Amplify and Forward

#### Decode and Forward

### Coordinated network

The idea of the coordinated network (CO) for 802.15.7r1 is to deploy multiple APs so that continuous coverage is reached 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, e.g. WiFi.

#### Modified frame structure

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| Figure – Frame structure in the coordinated network topology. |

#### Reference symbols for CO transmission

In order to identify different APs and UDs served by different APs in the CO topology, as an extension of the method in 802.11n, MIMO reference symbols are sent orthogonal also 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].

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| Figure - Reference symbols for channel estimation. Center: Over multiple reference symbols, each LED transmits another sequence. Subcarriers marked with the same color are assigned to the same access point. Subcarrier combs can be reused after a certain distance where the signal is attenuated enough. |

Using a comb of subcarriers, instead of pilot symbols on each subcarrier as in 802.11n, 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 reconstruct the channel frequency response based on such subcarrier combs [12]. Note that the same comb can be reused by another access point after a certain distance, at which the signal is sufficiently attenuated.

In the CO, and eventually also in the S topology, the MIMO reference signals are sent twice. In the first period, also denoted as cell-specific reference signal (CRS), the physical channel is estimated and used for transmitter optimization, after the AP received feedback from the UDs.

In the second period, also denoted as user-specific reference signal (URS), the training sequence is passed though the transmitter optimization, which can depend on the channel of other UDs as well. Only in this way, the UD can estimate the modified effective channel directly and adapt its receiver processing, accordingly.

#### CO transmission modes

#### Joint transmission

To be further detailed

#### Joint detection

To be further detailed

# Numerology

### Low-bandwidth mode

To be further defined.

### High-bandwidth mode

The numerology used in the high bandwidth mode is given in Table 1. It is based on specifications used for the coax cable transmission in the ITU G.hn standard [4, 5]. Similar to G.hn and 3GPP LTE, a variable bandwidth is used, while maintaining the same CP length and the same subcarrier spacing for all transmission modes. In this way, the wide range of user cases and the unprecedented span of data rates (i.e., from 1 Mbit/s to 10 Gb/s) can be addressed, as required in the TCD [8]. Note that for the peak and minimum data rates, it is assumed that all subcarriers are also loaded with data using the modulation schemes with the highest and lowest rate per subcarrier and the highest or lowest code rate is used, respectively. The 200 MHz mode is highlighted, as it is used in the performance evaluation in Section 7.

Owing to the adaptive bit-loading, eventually, a reduced number of subcarriers can be loaded only onto which the power will be redistributed, i.e. the minimum data rates can be even smaller. The huge span of bandwidth and modulation and coding schemes that can used in this proposal allow the transmitter to adapt the data rate to the huge variation of the received power and bandwidth being typical for the OWC channel in mobile scenarios. Even if the rate is adapted, connectivity can be maintained in all channel conditions.

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| |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | | Light source | Laser | Laser | **Laser/LED** | LED | LED | LED | | bandwidth [MHz] | 1.000 | 600 | **200** | 100 | 20 | 10 | | sample rate [MS/s] | 2.000 | 1.000 | **400** | 200 | 50 | 25 | | sample time [ns] | 0.5 | 1 | **2.5** | 5 | 20 | 40 | | carrier spacing [kHz] | 195.32 | 195.32 | **195.32** | 195.32 | 195.32 | 195.35 | | carriers in use | 4750 | 2850 | **950** | 450 | 90 | 45 | | IFFT size | 3x2.048 | 2x2.048 | **2048** | 1.024 | 256 | 128 | | CP [samples] | 640, 320 | 320, 160 | **128, 64** | 64, 32 | 16, 8 | 8, 4 | | CP [ns] | **320**, 160 | | | | | | | symbol duration [µs] | **5.12** | | | | | | | symbol + CP [ns] | **5.44**, 5.28 | | | | | | | peak rate [Mb/s]  (12 bit/carrier, r=20/21) | 9.975, 10.281 | 5985,  6.168 | **1.995**, 2.056 | 945,  1.028 | 189,  257 | 95,  103 | | min. rate [Mb/s]  (1 bit/carrier, r=1/6) | 145 | 87 | **35** | 14 | 3 | 1.4 |   Table - OFDM numerology for scalable bandwidth transmission. |

# Appendix: Performance Evaluation Results

## Simulation Framework

A modular simulation framework is used to simulate different parts of the entire link.

The framework can be adopted for a range of system modes including, but not limited to, those described in Table 1. All of the channel impulse responses (CIRs) provided in the *TG7r1 CIRs Channel Model Document for High-rate PD Communications* [6] can be used and performance can be evaluated for different scenarios.

## Peer-to-Peer

### Adaptive OFDM

The first simulation results address the *Scenario 4 Manufacturing Cell* using the 200 MHz mode as outlined in Table 1 with a long CP (see Table 2 for details). We have used CIRs in which all LEDs transmit simultaneously, and different diodes D1-D8 at the Rx. This is no limitation, and further results for other scenarios or individual CIRs can be provided upon request of the committee.

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| |  |  | | --- | --- | | Parameter | Value | | FFT size | 2048 | | Carrier spacing | 195.31 kHz | | Number of used sub-carriers | 950 | | Length of cyclic prefix | 128 (320 ns) | | Bits per carrier | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 | | Available modulation formats | BPSK, M-QAM (with ) | | Sub-carrier symbol rate | 183.82 kBd | | Modulation index | 10% | | Forward Error Correction | No, and LDPC from G.hn [4], information block size K=4320 and code rate 5/6 |   Table 2 - Parameters used for the simulations using the 200 MHz mode. |

### CIRs in the frequency domain

Normalized frequency responses are shown in Figure 7. Note that these plots (i.e., the CIR) are a superposition of the line-of-sight (LOS) and non-LOS (NLOS) components with different weight factors, so that a great variety of the path loss and the available channel bandwidth is commonly observed. The LOS component with a Dirac-like response offers the largest bandwidth, whereas the NLOS component due to specular and diffuse reflected lights results in a much reduced bandwidth typically yielding a low-pass response. As an example, the link with Rx D4 is dominated by a LOS channel whereas the link with Rx D7 is mostly dominated by the NLOS with the 3-dB bandwidth severely limited to around 10 MHz. One major implication for high-speed PD communications system design is the need for an adaptative scheme in terms of the variable path loss (which is normalized here) and large variations of the available bandwidth.

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| Figure 12 – Channel frequency responses normalized to DC gain for the receiver diodes Rx D1-D8. All LEDs transmit simultaneously. |

### PHY and MAC algorithms

For the P2P link, the simulation framework consists of DMT transmitter, linear channel determined by the aforementioned CIRs with additive white Gaussian noise and DMT receiver. The frame synchronization and channel estimation are considered to be ideal at this stage of the performance evaluation.

In a first iteration, the channel is probed by transmitting a BPSK signal with equal power distribution across all subcarriers. From the resulting channel estimation, the SNR per sub-carrier is obtained. The computationally efficient and optimal Krongold algorithm [7] is used to calculate the optimum bit and power loading for all subcarriers. A target un-coded bit error rate (BER) and a total power constraint are provided as inputs to the algorithm. The Krongold algorithm distributes the bits and power per subcarrier, thus resulting in a similar BER performance for all subcarriers in use. In the first step, no forward error correction (FEC) is used, while the target un-coded BER is set to . The ultimately chosen target BER will depend on the FEC code rate and the SNR margin used.

As an example, the SNR versus the subcarrier frequency and resulting bit- and power loading for an overall SNR of 28 dB is shown in Figure 9 (left) for the receiver at Rx D2. The resulting gross throughput of for this example is the total number of bits transmitted within one symbol period. Note that the bit- and power loading is less consistent when using the estimated, rather than ideal, channel knowledge. Figure 9d shows that, despite variable modulation formats used for each subcarrier, the algorithm realizes the expected bit error threshold with negligible fluctuation for all subcarrier indices.

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| Figure 13 – Bit and power loading results for the receiver diode D2 obtained from Krongold algorithm. The overall SNR is 28 dB and the target BER is .a) SNR per sub-carrier, b) bit loading distribution, c) power loading distribution, d) resulting uncoded BER per sub-carrier |

### BER vs. SNR using bit- and power loading

Using the same simulation framework, the CIRs corresponding to the 8 Rx D1-D8 were used and the SNR varied over a wide range. The hereby resulting average BER over all subcarriers in use is shown in Figure 10. At very low SNR, the number of active subcarriers is below 10. Thus there is a bit more fluctuation resulting from the low number of bits being transmitted. At high SNR, bit- and power-loading cannot load more bits onto the channel, as the maximum of 12 bits per symbol is already reached. Accordingly, a higher code rate which requires less bit errors can be used to increase the throughput. Rxs (e.g. Rx D1, D2, D6, D7) that receive the light mostly from diffuse reflections, with higher bandwidth limitations, reach this point but only at significantly higher SNR.

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| Figure 14 – Average bit-error rate at all diodes for different SNRs. At thigh SNR the targeted BER of is not achieved due to limitations in the modulation format cardinality. |

### Gross throughput results

Figure 11 shows this same behavior, in which the gross throughput is depicted in dependence of the overall SNR. Rxs mostly in a LOS path (Rx D3, D4, D5, D8) yield a steeper throughput increase as the overall SNR increases. Note that adaptive OFDM allows transmission also at unprecedented low SNR, compared to the non-adaptive system concepts. For lower SNR, fewer subcarriers are typically loaded with data symbols. As the path gain has its highest value always at low subcarrier frequencies, the bandwidth is automatically reduced at low SNR, while the same power is distributed over a smaller number of subcarriers. The redistribution of power to the lower subcarriers results in a higher power spectral density and it yields an increased distance that can be bridged with the optical wireless link.

It becomes obvious that dynamic link adaptation, with tradeoff between the link distance and the data rate, is a main enabler for improved mobility in high-rate PD communications. In particular, the number of active subcarriers can be reduced from around 960 down to 1, at least ideally. There is an enhanced dynamics range of 30 dB electrical (15 dB optical) in which the link can be operated in a robust mode, by reducing the data rate if the path loss is increased.

is a main enabler for improved mobility in high-rate PD communications. In particular, the number of active subcarriers can be reduced from around 950 down to 1, at least ideally. There is an enhanced dynamics range of 30 dB electrical (15 dB optical) in which the link can be operated in a robust mode, by reducing the data rate if the path loss is increased.

For the highly improved mobility reach in this manner, the dynamic bandwidth adaptation becomes mandatory not only for data transmission but also for the preamble and control information exchanged between the devices via the header. As a generic tool for bandwidth adaptation of the preamble and the header, FDZP with a variable padding factor *P* is proposed in Section 5.1.4.

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| Figure 15 – Gross throughputs in dependence of average signal-to-noise ratio. The inset shows the same graph with linear scaling of the throughput. |

### Relation between pre- and post FEC bit error rate

An important assumption in the proposed adaptive OFDM link is that the target bit error rate in the bit- and power loading algorithm is set correctly so that residual errors can always be corrected by the forward error correction (FEC).

In order to prove this, the complete link described in the previous section was extended using a low-density parity-check (LDPC) FEC, taken from the G.hn specification [4] with an information block size of 4320 and a code rate of 5/6.

In the manufacturing cell scenario, a PD was selected having a SNR variation of up to 15 dB in the considered range of modulation frequencies, see Rx D2 in Figure 9. For a fixed SNR of 28 dB, which is the same as considered in 7.2.2, the target error rate in the Krongold algorithms has been varied from 1e-3 to 1e-1. Then, the BER in front of the FEC decoder was measured to verify that the targeted BER is reached as well as the BER after the decoder.

More than 20 million bits was transmitted for each value of the BER threshold in order to measure the two BERs. In order to limit the simulation effort, it is assumed that blocks that cannot be decoded correctly are requested again, using the “selective repeat” mechanism that is available in G.hn. As shown in Figure 13, obviously, the aforementioned BER threshold of 10-2 is sufficient so that all transmitted packets can be correctly decoded. Due to the overhead introduced by the LDPC code, however, the gross throughput results in Figure 12 have to be multiplied by factor 5/6 in order to get the net throughput.

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| Figure - Input vs. Output bit error rate characteristics after using forward error correction (FEC) with code rate 5/6. |

## Singlecarrier modulation

Precoding is proposed as an option in 5.1.7.1 to improve the peak-to-average-power ratio (PAPR) of the adaptive OFDM waveform. It is mainly desirable in the uplink from the UD to the AP, where each UD has its own frequency sub-band assigned by the AP and could improve its own PAPR by optimizing the waveform.

The evaluation in this section is entirely made at the transmitter side, and does not take into account the channel model.[[5]](#footnote-5) More detailed information can be found in [2, 3].

For comparison, waveforms were created in MATLAB. Examples of the waveforms and the corresponding PAPR statistics are shown in Figure 14 and Figure 15, respectively. The envelope flutuation can be reduced step by step. Already by using *π/2* BPSK, the fluctuation in the waveform is reduced compared to the SC-FDMA scheme used in the LTE standard. However, despite the envelope fluctuation is significantly smaller than for OFDMA, the 99-percentile of the cumulative PAPR statistics is still around 5 dB.

see Fig. 3, right. Substantial back-off is still needed to avoid

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| Figure left: Real value of exemplary singlecarrier waveforms. Right: Corresponding traces in the complex plane. A: π/2 BPSK modulation. B: Root-raised-cosine (RRC) filtering. C: Same but using π/2 BPSK modulation. D: GMSK with time-bandwidth product of 0.3, same as in the GSM standard. |
| Figure Comparison of the peak-to-average power ratio (PAPR) statistics measured in the complex IQ plane for several singlecarrier waveforms. Same colors were used as in Figure 14. |

Using filtered BPSK with a roll-off factor of 0.7, the filtered data sequence is also the envelope, see Figure 14, B. Most of the time, the amplitude is within a small range. But there are zero-crossings during constellation-point changes between two symbols. Therefore, the envelope is not constant and certain fluctuations remain. Altogether, the 99-percentile of the cumulative PAPR statistics is around 3.5 dB in this way, see Figure 15.

Filtered *π/*2–BPSK reduces these envelope fluctuations further, see Figure 14, C. Introducing GMSK, finally, a constant envelope can be obtained, see Figure 14, D, where the PAPR is 0 dB. Clearly, this is a common property of all sontinuous phase modulation (CPM) schemes, including GMSK. The contribution in [3] was to integrate GMSK seamlessly into the localized SC-FDMA framework developed for LTE.

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| Table 3 PAPR values measured in the complex IQ plane of different singlecarrier modulation schemes. |

Table 3 lists the PAPR values for different modulation and precoding schemes that were obtained by numerical simulation. It becomes obvious that the gains compared to OFDMA are really significant, when using modulation schemes with small spectral efficiency, such as GMSK and *π/*2–BPSK, together with and appropriate filtering with relatively high roll-off factor. However, as the modulation scheme becomes more complex, such as 16- or 64-QAM, the gains are reduced. The reason for this observation is that the constellation points used by these modulation formats do already have varying instantaneous power levels, leading to an intrinsic contribution of the modulation scheme to the PAPR, beside the one due to the waveform over which the constellation points are transmitted. Moreover, there is a loss of spectral efficiency in general, as the filtering needs 20-25% more bandwidth.

According to these results, it is proposed to use DFT precoding and GMSK modulation as the most robust available transmission scheme for transmitting e.g. the header information, the RRC-filtered versions of *π/*2–BPSK and *π/4*–QPSK with higher roll-off factor and the original DFT-precoded versions of M-QAM without filtering when M>4.

## Unipolar modulation

Tbd.

## MIMO

Tbd.

## Star

Tbd.

## Coordinated Network

Tbd.

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1. Scenario B1-B4 in TCD [8]. [↑](#footnote-ref-1)
2. Consistency can be checked by measuring the error vector magnitude (EVM) in front of the demodulator. [↑](#footnote-ref-2)
3. In Matlab, this is the function floor(*z*). [↑](#footnote-ref-3)
4. 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-4)
5. It is noted that the impact of reduced PAPR onto the clipping of the waveform as well as onto non-linear distortions, due to the power-vs.-current characteristics of the LED, resulting in the generation of in-band and out-of band interference, cannot be characterized by the linear channel model agreed upon in TG7r1 so far. Upon request by the task group, HHI is willing to contribute to developing such a model and to compare the performance of the proposed precoding with other proposals if this is needed. It is understood that a sufficient time for setting up the model and performing these simulations is allowed by the committee. [↑](#footnote-ref-5)