**IEEE P802.15**

**Wireless Personal Area Networks**

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| 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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|  |  |
|  |  |

[1 Overview 5](#_Toc440735404)

[1.1 Scope 5](#_Toc440735405)

[1.2 Purpose 5](#_Toc440735406)

[2 Normative references 5](#_Toc440735407)

[3 Definitions, acronyms and abbreviations 6](#_Toc440735408)

[3.1 Definitions 6](#_Toc440735409)

[3.2 Acronyms and Abbreviations 6](#_Toc440735410)

[4 General description 8](#_Toc440735411)

[4.1 Introduction 8](#_Toc440735412)

[4.2 Network Architecture 8](#_Toc440735413)

[4.2.1 Introduction 8](#_Toc440735416)

[4.2.2 Network topologies 8](#_Toc440735417)

[4.2.2.1 Standalone link 9](#_Toc440735418)

[4.2.2.2 Multiuser link 9](#_Toc440735419)

[4.2.2.3 Coordinated link 9](#_Toc440735421)

[4.2.3 General features 9](#_Toc440735422)

[4.2.3.1 Data rates 9](#_Toc440735423)

[4.2.3.2 Efficiency use of optical bandwidth 10](#_Toc440735424)

[4.2.3.3 Advanced wireless networking 10](#_Toc440735425)

[5 PHY 10](#_Toc440735426)

[5.1 Standalone SISO link 10](#_Toc440735427)

[5.1.1 SA PHY frame 11](#_Toc440735428)

[5.1.2 SA Preamble 11](#_Toc440735429)

[5.1.3 SA Header 12](#_Toc440735430)

[5.1.4 Used-bandwidth adaptation 12](#_Toc440735431)

[5.1.5 SA Waveform 12](#_Toc440735433)

[5.1.5.1 OFDM signal generation 12](#_Toc440735434)

[6.1.1.1 Precoding (optional) 12](#_Toc440735435)

[6.1.1.2 IFFT 12](#_Toc440735436)

[6.1.1.3 Carrier mapping in SA mode 13](#_Toc440735437)

[6.1.1.4 CP insertion 13](#_Toc440735438)

[6.1.1.5 Numerology 13](#_Toc440735439)

[6.1.1.6 Interoperability between PHY modes with different bandwidths 14](#_Toc440735440)

[6.1.2 MIMO, CSK and WDM 14](#_Toc440735441)

[6.1.2.1 Channel estimation for MIMO 14](#_Toc440735442)

[6.1.2.2 Channel estimation for CSK and WDM 15](#_Toc440735443)

[6.1.3 Channel coding 15](#_Toc440735445)

[6.1.3.1 Channel coding in the header 15](#_Toc440735446)

[6.1.3.2 Channel coding for data 15](#_Toc440735447)

[6.1.3.3 Channel coding for MIMO 15](#_Toc440735448)

[6.2 Multiuser link 15](#_Toc440735449)

[6.2.1 PHY support for TDMA 16](#_Toc440735450)

[6.2.1.1 Generation of feedback and control messages 16](#_Toc440735451)

[6.2.2 Uplink synchronization for FDMA 16](#_Toc440735452)

[6.2.2.1 Ranging 16](#_Toc440735453)

[6.2.3 PHY support for FDMA 16](#_Toc440735454)

[6.2.3.1 Generation of feedback and control messages 16](#_Toc440735455)

[6.2.4 PHY support for coordinated transmission 16](#_Toc440735456)

[6.2.4.1 Generation of feedback and control messages 16](#_Toc440735457)

[6.2.4.2 Joint transmission 16](#_Toc440735458)

[6.2.4.3 Joint detection 16](#_Toc440735459)

[7 MAC 16](#_Toc440735460)

[7.1 Standalone link 16](#_Toc440735461)

[7.1.1 SA Initial link setup 16](#_Toc440735462)

[7.1.2 SA Feedback messages on reverse link 16](#_Toc440735463)

[7.1.3 SA Control messages on forward link 16](#_Toc440735464)

[7.2 Multiuser link 17](#_Toc440735465)

[7.2.1 MU Initial link setup 17](#_Toc440735466)

[7.2.2 TDMA, FDMA, SDMA 17](#_Toc440735467)

[7.2.3 MU Feedback messages on reverse link 17](#_Toc440735468)

[7.2.4 MU Control messages on forward link 17](#_Toc440735469)

[7.3 Coordinated link 17](#_Toc440735470)

[7.3.1 TDMA, FDMA, SDMA 17](#_Toc440735471)

[7.3.2 CO Initial link setup 17](#_Toc440735472)

[7.3.3 CO Feedback messages on reverse link 17](#_Toc440735473)

[7.3.4 CO Control messages on forward link 17](#_Toc440735474)

[7.3.5 CO Feedback- and control messages transport over the fronthaul 17](#_Toc440735475)

[8 Performance evaluation results 17](#_Toc440735476)

[8.1 Simulation framework 17](#_Toc440735477)

[8.2 Standalone link 18](#_Toc440735478)

[8.3 Multiuser link 22](#_Toc440735479)

[8.4 Coordinated link 22](#_Toc440735480)

[9 References 23](#_Toc440735481)

# Overview

## Scope

This proposal defines PHY and MAC layers for *high rate photodiode communications* in a next-generation optical wireless communications (OWC) 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 802.15.7 proposal for visible light communication (VLC) 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 (OFDM), adaptive transmission, multiple-input multiple-output (MIMO) and coordinated links to provide mobility for mobile users in an OWC based network. Furthermore, this proposal enables the coexistence of OWC with radio based wireless 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 link

C-RAN cloud radio access network

CRS cell-specific reference signal

CSK color shift keying

DAC digital-to-analog conversion

DFT discrete Fourier transform

DMT discrete multi-tone

DSP digital signal processor

FDMA frequency-division multiple access

FDZP frequency-domain zero-padding

FEC forward error-correction

FFT fast Fourier transform

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

MU multiple user

NC network controller

NLOS non-line-of-sight

OFDM orthogonal frequency-division multiplexing

OWC optical wireless communication

P2P peer-to-peer

PD photodiode

PHY physical layer

SISO single-input single-output

SNR signal-to-noise ratio

TDMA time-division multiple access

URS user-specific reference signal

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 OWC in order to address the specific requirements of new user cases in new scenarios[[1]](#footnote-1) mentioned in the TCD for 802.15.7r1 [8], such as a wireless access in indoor/home/office, industrial wireless (with specific requirements for high robustness and low latency), secure wireless transmission, communications between vehicle to vehicle and vehicle-to-the-roadside-infrastructure communications, and as a wireless backhaul technology.

## 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

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| \\hhi.de\abteilung\PN\Groups\Metro, Access  and In-house Systems\Projekte\IEEE 802.15.7r1\Proposals\Bilder\PNG\Sicherungskopie_von_standalone multiuser coordinated links.pngFigure - Topology of standalone, multiuser and coordinated links |

In addition to standalone (SA) and multiuser (MU) topologies described in 802.15.7, this proposal supports additional coordinated (CO) links, enabling mobility among multiple access points (APs), i.e. handover and interference coordination. The topologies are shown in Figure 1.

In the SA link, two user devices (UDs) can connect to each other and establish a transparent wireless link.

In the MU link, one UD acts as AP serving multiple other UDs in parallel. The AP aggregates the traffic from UDs and coordinates their wireless transmission.

In the CO link, multiple UDs are served by multiple APs, which are in turn coordinated by a central network coordinator (NC). The NC manages the interference, reroutes the traffic path between NC and APs in case of handover and controls the transmission of all APs and UDs. The NC also aggregates the wireless traffic of all APs towards the network.

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

Note that the coordination algorithms for MU and CO topologies are not part of this proposal. Rather, the wireless link is defined , which includes the required reference signals and the control channels so that the feedback from the UDs is available at APs and the NC, and APs and UDs can respond in real-time to control messages sent out by the AP and NC.

#### Standalone link

The SA link is defined such that it may serve as a wireless replacement of an Ethernet cable in any computer or telecommunication networks. Besides the PHY, the only MAC layer issues to be defined are the automatic link setup and the feedback path required for closed-loop link adaptation. No NC and AP functionality are required in the SA topology.

#### Multiuser link

The MU link requires additional PHY and MAC functionalities, in particular the support for synchronized MU transmission in the uplink. The feedback from MUs has to be transmitted in an orthogonal manner, i.e., without contention whenever possible. An additional control channel is needed, which is broadcast to all MUs in order to inform each device about the granted transmission interval in both link directions. Dynamic bandwidths sharing among MUs is supported in a controlled manner in both directions.

#### Coordinated link

In the CO link, all APs are operated in a time-synchronized manner. MUs and APs are enabled to estimate the physical interference channel in both link directions. The respective measurement reports are conveyed to the NC via the APs and over the fronthaul. This information is required at NC for interference coordination and handover. By additionally knowing the interference conditions, transmission can be optimized, as interference is avoided and can even become a useful signal.

### General features

#### Data rates

This proposal supports variable data rates from 1 Mbit/s to 10 Gbit/s, depending on the use case. This is achieved in principle using OFDM with a variable number of subcarriers, together with adaptive bit- and power loading using variable modulation formats on each subcarrier or on groups of subcarriers, depending on the channel-, interference- and noise-characteristics of the OWC link.

#### Efficiency use of optical bandwidth

This proposal supports the efficient use of the optical bandwidth. This includes robustness against the multi-path propagation channel, which is addressed using closed-loop adaptive transmission and MIMO technology. Moreover, PHY and MAC layer are defined so that latencies less than 1 ms are achievable for data rates of 100 Mb/s and above.

#### Advanced wireless networking

Feedback and control channels are defined so that transmission is robust for all channel conditions. The link is available also in line-of-sight (LOS) and non-LOS (NLOS) scenarios at low signal-to-noise ratio (SNR). Moreover, the control plane information is made easily available to higher layer protocols, which enable advanced wireless networking in both MU and CO topologies.. Short time intervals between feedback and control messages are enabled to allow low latency and instantaneous adaptation to the time-varying wireless channel.

# PHY

## Standalone SISO link

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

An overview of the SA link is shown in Figure 2. At the transmitter (Tx), the parallel input data streams is transported via the orthogonal subcarriers. Each data symbol (containing one or more bits) is mapped onto a constellation point, according to a variable modulation format for each subcarrier. The mapping of information bits onto the sub-carriers is based on the feedback information, which carry a so-called noise enhancement vector, and received over the reverse link direction. A loading algorithm determines the power and modulation formats for the data transport on each data stream. An OFDM symbol is finally generated by means of digital signal processing. Samples in the time domain are fed into the inverse fast Fourier transform (IFFT) followed by the insertion of a cyclic prefix (CP). The output of the OFDM is then passed through the digital-to-analog converter (DAC) and low-pass filter (LPF), prior to intensity modulation of the optical source (i.e., light emitting diode (LED) or a laser diode (LD)). Note that a DC bias is added to ensure a unipolar all positive signal. Following signal detection and conversion from optical to electrical signal, the inverse operations are performed at the receiver (Rx), where an additional frequency-domain equalizer is used to reconstruct the received constellation on each sub-carrier, after passing it through the optical wireless channel.

### SA PHY frame

The data signal is transmitted as a compound frame as shown in Figure 3, which can be decoded frame-wise. The SA preamble allows coarse synchronization and channel estimation, thus enabling the Rx to decode the SA header information. The SA 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 frame may also contain additional reference signals that could be used to correct distortion due to the sampling frequency offset between low-cost reference clocks.

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| Figure – SA PHY frame. |

### SA Preamble

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

For optimization in low SNR, modifications are considered, like the one 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 time metric by using the Schmidl-Cox algorithm [10]. Optimization allows more accurate synchronization and improved robustness against the noise and multipath.

The final OFDM symbol in the preamble is used for channel estimation. It is used in general to detect the header information and for SISO also for the detection of data. In case MIMO is used in the SA link, and in MU 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.

### SA Header

SA header information is generally defined in the MAC layer, see Section 6. Header information is normally transported using OFDM.

For optimization in low SNR, pre-coding can be used (see Section 5.1.5.2). The same CP duration like in the last preamble symbol for channel estimation is used.

### Used-bandwidth adaptation

Used-bandwidth adaptation is introduced for optimization in low SNR and controlled by MAC layer via commands sent in the header, see Section 6. More reliable transmission may be reached by reducing the signal bandwidth. One generic way is to reduce the number of active subcarriers and to redistribute the available power over all active subcarriers. This is, however, possible only for signals entirely defined in the frequency domain using OFDM. For signals are defined in the time domain, a different procedure is needed. Frequency-domain zero-padding (FDZP) is used in this case. For instance, consider the preamble excluding the last symbol for channel estimation. This block can be passed through an NP-point IDFT, with *P*\*NP-zero being appended, where *P* is the padding factor, and the result is fed into an (1+*P*)\*NP point DFT. This procedure stretches the signal in the time domain and reduces the bandwidth by factor P.

### SA Waveform

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

i) The generation of non-negative real-valued waveforms

ii) Optional precoding to improve power efficiency

iii) An optional bias current to drive the LED

#### OFDM signal generation

1. OFDM signal generation is shown in Figure 4. Following an optional pre-coding, the signal is passed through a carrier mapping unit for performing the Hermitian symmetry operation, the IFFT and the CP modules. A block of 2*N* data symbols is transmitted, where *N* is always a power of 2. For the 1 GHz mode defined in Table 1, the IFFT block size 2*N* = 6144.

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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.pngFigure - OFDM signal generation |

#### Precoding (optional)

Here, optional functionalities, which are to be inserted in front of the OFDM modulator, are described leading to reduced probability of clipping and enhanced power efficiency, following the potential evolution of SC-FDMA in 3GPP LTE developed in [2, 3].

To be further detailed, see [2, 3].

#### IFFT

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

$$X\left(k\right)=\frac{1}{2N}\sum\_{n=0}^{2N-1}x\_{n}e^{j2π\frac{nk}{2N}}$$

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

#### Carrier mapping in SA mode

In the SA topology, 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

$x\_{2N-i}=x\_{i}, i=1,2,…N-1$.

The resulting discrete multi-tone (DMT) signal is real-valued, even if the 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.pngFigure - Carrier mapping for standalone link |

#### CP insertion

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.

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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.pngFigure - Cyclic Prefix insertion |

#### Numerology

The numerology given in Table 1 is exemplary and 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) are 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, respectively. Owing to bit-loading, eventually, reduced number of subcarriers can be loaded than necessary, so that the minimum data rates can be much smaller in practice.

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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. |

#### Interoperability between PHY modes with different bandwidths

A transceiver with a small bandwidth can synchronize with respect to, and exchange control information with, another transceiver having a high bandwidth, and vice versa, by switching both transceivers to the lower bandwidth mode.

### MIMO, CSK and WDM

#### Channel estimation for MIMO

Training symbols for MIMO channel estimation are defined in the frequency domain and over multiple OFDM symbols. All OFDM symbols have the same numerology as the used for the data. In general, the MIMO preamble is sent at the beginning of the data block.

Definition of training symbols in the frequency domain is used to identify different APs in the CO topology. For MIMO, the same training symbol is used but multiplied as a whole with another sign taken out of an orthogonal sequence, as in the IEEE 802.11n standard. Channel estimation is performed using correlation, at the same subcarrier, over multiple OFDM symbols.

In the CO topology with multiple APs, which can be considered as a virtual MIMO link, the number of transmitters grows substantially. Hence, the goal is to define suitable reference signals and keep the overhead manageable. The general approach is that, during the entire channel estimation block duration, each AP is assigned a comb of subcarriers (marked with the same specific color in Figure 7), from a set of mutually orthogonal combs [11].

Using a comb of subcarriers, instead of pilot symbols on each subcarrier like in 802.11n, is possible because only as many subcarriers are needed for channel estimation as there are taps in the CP. Advanced computationally efficient algorithms are available in the literature in order to accurately reconstruct the channel frequency response for well-designed subcarrier combs [12].

Note that the same comb can be reused by another access point after a certain distance, after which the signal is sufficiently attenuated. Using a comb of subcarriers, instead of pilot symbols on each subcarrier like in 802.11n, is possible in general. In order to identify the channel, at least as many subcarriers are needed, as there are taps in the CP. Advanced computationally efficient algorithms are available in the literature in order to reconstruct the channel frequency response for well-designed subcarrier combs precisely [11].

In the MU and CO topology, it is often necessary to send the MIMO training sequence twice from the AP to the UDs. In the first period, the physical channel is estimated and used for transmitter optimization, after the AP received feedback information from the UDs. The first period is also denoted as cell-specific reference signal (CRS). In the second period, 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 and adapt its receiver processing, accordingly. The second period is also denoted as user-specific reference signal (URS).

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|  **frequency****time**Figure - Reference symbols for channel estimation. The subcarriers marked with the same color are assigned to the same access point. |

#### Channel estimation for CSK and WDM

Note that channel estimation for color shift keying (CSK) and wavelength-division multiplex (WDM) can be implemented with the same concept. LEDs occupy a wide optical spectrum. Therefore, in order to reduce cross-talk following color filtering at the Rx, each Tx is assigned a different orthogonal code, as in MIMO. This enables efficient color calibration as well.

### Channel coding

#### Channel coding in the header

To be further detailed.

#### Channel coding for data

Low-density parity-check coding (LDPC) according to the G.hn standard is used, see [4].

To be further detailed.

#### Channel coding for MIMO

To be further detailed

## Multiuser link

MU transmission is supported in time-division multiple access (TDMA) mode. Frequency-division multiple access (FDMA) is only optional, and useful to achieve ultra-low latency and multiuser diversity by means of concurrent transmission for multiple users. In the MU uplink, therefore, additional synchronization among the users is needed for FDMA.

### PHY support for TDMA

#### Generation of feedback and control messages

To be further detailed

### Uplink synchronization for FDMA

#### Ranging

To be further detailed

### PHY support for FDMA

#### Generation of feedback and control messages

To be further detailed

### PHY support for coordinated transmission

#### Generation of feedback and control messages

To be further detailed

#### Joint transmission

To be further detailed

#### Joint detection

To be further detailed

# MAC

## Standalone link

### SA Initial link setup

To be further detailed

### SA Feedback messages on reverse link

To be further detailed

### SA Control messages on forward link

To be further detailed

## Multiuser link

### MU Initial link setup

To be further detailed

### TDMA, FDMA, SDMA

To be further detailed

### MU Feedback messages on reverse link

To be further detailed

### MU Control messages on forward link

To be further detailed

## Coordinated link

### TDMA, FDMA, SDMA

### CO Initial link setup

To be further detailed

### CO Feedback messages on reverse link

To be further detailed

### CO Control messages on forward link

To be further detailed

### CO Feedback- and control messages transport over the fronthaul

To be further detailed

# Performance evaluation results

## Simulation framework

A simulation framework of high modularity is used to simulate different parts of the entire system setup. The simulation 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.

## Standalone link

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 $N\_{FFT}$ | 2048 |
| Carrier spacing $Δf$ | 195.31 kHz |
| Number of used sub-carriers $N\_{ch}$ | 950 |
| Length of cyclic prefix $N\_{CP}$ | 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 $M=2^{m}, m=2…12$) |
| Sub-carrier symbol rate $R\_{S}$ | 183.82 kBd |
| Modulation index | 10% |

Table 2 - Parameters used for the simulations using the 200 MHz mode. |

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

For the SA 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, carrier phase offset correction 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 $10^{-2}$. 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 $6.232 bits⋅R\_{S}=1.15 Gb/s$ 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 9 – 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 $10^{-2}$.a) SNR per sub-carrier, b) bit loading distribution, c) power loading distribution, d) resulting uncoded BER per sub-carrier  |

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 10 – Average bit-error rate at all diodes for different SNRs. At thigh SNR the targeted BER of $10^{-2}$ is not achieved due to limitations in the modulation format cardinality. |

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

## Multiuser link

tbd

## Coordinated link

tbd

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