**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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# Overview

## Scope

This proposal defines PHY and MAC layers for *high rate photodiode communications* in a next-generation optical wireless communication (OWC) system. This proposal is capable to support fixed wireless links and multiple mobile user links to an optical wireless infrastructure consisting of one or more wireless access points. This proposal supports a wide variety of data rates, ranging from 1 Mb/s to 10 Gb/s, targeting an efficient use of the available optical bandwidth under variable channel conditions. This proposal also describes unified interfaces for user plane and control plane information that 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 also below 380 and above 780 nm, hereby including the invisible light. Moreover, this proposal introduces new transmission modes for higher data rates up to 10 Gbit/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 optical wireless network. Furthermore, this proposal enables the coexistence of optical wireless links with radio.

# 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

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

WDM wavelength-division multipex

# General description

## Introduction

This proposal extends the capabilities and improves the transmission performance of OWC in order to address the specific requirements of new use 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 vehicles and vehicles and a roadside communication infrastructure and as a wireless backhaul technology.

## Network Architecture

### Introduction

### Network topologies

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| Figure - Topology of standalone, multiuser and coordinated links |

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

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

In the MU link, one device acts as AP serving multiple users in parallel. The AP aggregates the traffic from multiple users and controls their wireless transmission.

In the CO link, multiple users 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 it controls the transmission of all APs and MUs aggregates also the wireless traffic 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 over time, starting with the SA configuration and subsequently including the functionality required for MU and CO modes.

Note that the coordination algorithms for MU and CO topologies are not part of the proposal. Rather, the wireless link is defined including the required control plane information so that the feedback is made available at the AP and NC and that APs and MUs can respond in real-time to the 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 network. Besides the PHY, the only MAC layer issues to be defined are the automatic link setup and the feedback required for closed-loop link adaptation. No NC and AP functionality are required in SA mode.

#### Multiuser link

The MU link requires additional PHY and MAC functionalities, in particular 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 so that each device is informed 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 both for the downstream and upstream directions. This information is conveyed to the NC via the APs and the fronthaul. The NC needs this information for interference coordination and handover. By additionally knowing interference conditions, transmission can be optimized, interference avoided and even exploited.

### 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 modulation with a variable number of subcarriers, together with adaptive bit- and power loading using variable modulation formats on subcarriers or subcarrier groups, depending on the channel-, interference- and noise-characteristics of the wireless link.

#### Efficiency use of optical bandwidth

This proposal supports an efficient use of the optical bandwidth. This includes robustness against multi-path propagation in the OWC channel and is addressed by means of closed-loop adaptive transmission and the support of MIMO technology. Moreover, PHY and MAC layer are defined so that latencies below 1 ms are achievable for data rates of 100 Mbit/s and above.

#### Advanced wireless networking

Feedback and control channels are defined so that transmission is robust in all channel realizations. Moreover, control plane information is made easily available to higher layer protocols that enable advanced wireless networking in MU and CO modes. Short time intervals between feedback and control messages 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 Tx, the input data runs in parallel streams transported via 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 sub-carriers is based on feedback information, carrying a so-called noise enhancement vector, received over the reverse link direction. A loading algorithm determines power and modulation format for the data transport on each stream. An OFDM symbol is finally formed by digital signal processing. Samples in the time domain are fed into the inverse fast Fourier transform (IFFT), after which a cyclic prefix (CP) is added. After passing the samples through a digital-to-analog converter (DAC) and low-pass filter (LPF), the signal is used to directly modulate the optical source, which can be a light emitting diode (LED) or a laser diode (LD). The inverse operations are performed at the receiver, 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

Data are transmitted as a compound frame as shown in Figure 3, that can be decoded frame-wise. The SA preamble allows coarse synchronization and coarse channel estimation enabling the receiver to decode SA header information. The SA header contains the control plane information needed to setup the link and to decode the subsequent data packet. Next, there is a block which contains reference signals for channel estimation. Finally, there is the data block. It may contain additional reference signals 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 coarse channel estimation so that the header can be correctly decoded. The SA preamble is composed of six consecutive short sequences 𝐴*NP/6*, where NP denotes the total preamble length and 𝐴*NP/6* is a random sequence, organized as [𝐴*NP/6*, 𝐴 *NP/6*, −𝐴 *NP/6*, 𝐴 *NP/6*, −𝐴 *NP/6*, −𝐴*NP/6*].

In [9], the preamble has been optimized to create a sharp time metric, assuming that the Schmidl-Cox algorithm [10] is used, to allow more accurate time synchronization and improved robustness against noise and multipath, compared to the original [𝐴*NP/2*, 𝐴 *NP/2*] preamble. Optimal selection of 𝐴*NP/6* for 802.15.7r1 and the best value of NP are for further study.

A CP is also appended, like for data (see Section 5.1.5.5) but the length of the CP may differ from the one used for data.

### SA Header

SA header information is generally defined in the MAC layer. Header information is transported using OFDM with optional pre-coding (see Section 5.1.5.2) by using the same CP duration like in the preamble. Eventually, carrier spacing is increased so that control overhead is minimized.

### Frequency-domain zero padding for preamble and header

In poor channel conditions, reliable link setup and signaling are enabled by reducing the preamble and header bandwidth in a generic manner. This is achieved using an interpolation technique known as frequency-domain zero-padding (FDZP).

The preamble is passed through an NP-point IDFT, P\*NP zeros are appended, where P is the padding factor, and the result is fed into an (1+P)\*NP point DFT.

The header is passed through an NH-point IDFT, P\*NH zeros are appended, and the result is fed into an (1+P)\*NH-point DFT.

This procedure increases the number of samples and reduces the used signal bandwidth. Preamble and header detection need to take this into account. Note that this technique is not applied to the reference symbols for the channel estimation and for the data.

### SA Waveform

The standalone PHY uses 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

OFDM signal generation is shown in Figure 4. Following an optional precoding, there is a carrier mapping unit, performing the Hermitian symmetry operation, an IFFT and the cyclic prefix is added. A block of 2N data symbols is transmitted, where N is always a power of 2. In the 1 GHz mode defined in Table 1, 2N=6144.

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| Figure - 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

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 SA mode, 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 the symbols *xn* are complex.

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| Figure - 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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| Figure - Cyclic Prefix insertion |

#### Channel estimation

To be further detailed.

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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. |

#### Numerology

The numerology given in Table 1 is exemplary and based on specifications used for 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 lengths and the same subcarrier spacing for all transmission modes. In this way, the wide variety of use cases and the unprecedented span of data rates ranging from 1 Mbit/s to 10 Gbit/s are addressed, as required in the TCD [8]. Note that for 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, less subcarriers can be loaded than used, so the minimum data rates can be much smaller in practice.

### Interoperability between PHY modes with different bandwidth

Note that FDZP introduced in Section 5.1.4 allows another new feature. By using the appropriate repetition factors R in each transceiver, 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. Control plane information is always transmitted in a matched-bandwidth mode, while data transmission is restricted to the same number of active subcarriers, even if the number of used subcarriers, as given in Table 1, may differ in both transceivers.

### MIMO, CSK and WDM

#### Preamble for MIMO, CSK and WDM channel estimation

The preamble for MIMO channel estimation is defined in the frequency and time domains. It consists of a sequence of OFDM symbols having the same numerology as the one used for data.

In the time domain, each MIMO transmitter is assigned another sequence out of an orthogonal set of sequences, like in the IEEE 802.11n standard. Channel estimation is then performed using correlation, at the same subcarrier, over multiple OFDM symbols.

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. In order to reduce cross-talk behind color filters at the receiver, each transmitter is assigned another orthogonal code, similar like in a MIMO link. Efficient color calibration can be implemented in this way.

A coordinated link with multiple access points increases the number of MIMO transmitters even more. The goal is to define suitable reference signals and keep the overhead manageable. The general approach is that each access point is assigned one comb of subcarriers assigned a specific color in Figure 7, out of an orthogonal set of combs, during the whole channel estimation block duration. 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].

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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 coding

#### Channel coding for control plane information

To be further detailled.

#### Channel coding for data

Low-density parity-check coding (LDPC) according to the G.hn standard is used for performance evaluation of adaptive OFDM transmission, see [4].

To be further detailled.

#### Channel coding for MIMO transmission

To be further detailled

## 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 more complex MU and CO link scenarios make use of the underlying framework used for the SA link, which is based on the physical layer as defined in 5.1. The simulation framework allows for a variety 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 in different scenarios.

## Standalone link

The first simulation results address the *Scenario 4 Manufacturing Cell* using the 200 MHz mode from Table 1 with a long cyclic prefix (see Table 2 for details). Those CIRs were used, in which all LEDs transmit simultaneously, while each of the different receiver diodes Rx D1-D8 are used. 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% |   Table 2 - Parameters used for the simulations using the 200 MHz mode. |

Normalized frequency responses are shown in Figure 7. As it is well known for optical wireless channels, they are a superposition of line-of-sight (LOS) and non-LOS (NLOS) components. Where the LOS component creates a Dirac-like response with wide bandwidth, while the NLOS component is related to specular and diffuse reflected light typically yielding a low-pass response. In most cases, the CIR contains both such components superimposed to each other with different weight factors, so that a great variety of the path loss and the available channel bandwidth is commonly observed. For instance, Rx D4 is dominated by a LOS channel while Rx D7 receives most light via reflections and therefore the bandwidth is severely limited to around 10 MHz measured at the 3 dB point. One major implication for high-speed PD communications system design is that an appropriate adaptation is needed not only to the variable path loss (which is normalized out here) but essentially also to 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 a DMT transmitter, a linear channel determined by the aforementioned CIRs with additive white Gaussian noise and a DMT receiver. The frame synchronization, carrier phase offset correction and channel estimation can be included by are considered ideal at this stage of the performance evaluation.

In a first iteration, the channel is probed by transmitting a BPSK signal having equal power distribution on all subcarriers. From the resulting channel estimation, the signal-to-noise ratio (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 BER and total power constraint are provided as inputs to the algorithm. The Krongold algorithm distributes the bits and power per subcarrier, resulting in a similar bit-error performance of all subcarriers in use. In a first step, no forward error correction (FEC) is used, while the target uncoded bit-error rate (BER) is set to . The ultimately chosen target BER will depend on the FEC codes and SNR margin used.

As an example, the SNR versus the subcarrier frequency and resulting bit- and power loading at an SNR of 10 dB is shown in Figure 8 (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 estimated, rather than ideal channel knowledge. Figure 8d it is shown that, despite variable modulation formats used for each subcarrier, the algorithm realizes the expected bit error threshold with negligible fluctuation for all sub-carrier 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 10dB and the target BER is .a) SNR per sub-carrier, b) bits loading distribution, c) power loading distribution, d) resulting uncoded BER per sub-carrier |

Using the same simulation framework, the CIRs corresponding to the eight receiver diodes Rx D1-D8 where used and the SNR varied over a wide range. The hereby resulting average BER over all carriers in use is shown in Figure 9. At very small SNR, the number of active subcarriers is below 10. Thus there is little more fluctuation resulting from the low number of bits 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. Receivers that receive the light mostly from diffuse reflections with higher bandwidth limitations (e.g. Rx D1, D2, D6, D7) 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 is not achieved due to limitations in the modulation format cardinality. |

Figure 10 shows this same behavior, in which the gross throughput is depicted in dependence of the overall SNR. Having the receiver mostly in a line of sight channel condition (Rx D3, D4, D5, D8) yields a steeper throughput increase as the overall SNR increases. Note that adaptive OFDM allows transmission also at unprecedented low SNR, compared to non-adaptive system concepts. If the SNR is lower, 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 its automatic tradeoff between link distance and 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 path loss is increased.

For the greatly improved mobility reached in this way, 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 variable padding factor P is proposed in Section 5.1.4.

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| P:\Groups\Metro, Access  and In-house Systems\Projekte\IEEE 802.15.7r1\Proposals\Bilder\simulation\throughput_vs_snr_manufacturingCell_simultaneously.eps  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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