IEEE P802.15.7a™/D8 Draft Standard for Local and Metropolitan Area Networks—Part 15.7: Short-Range Optical Wireless Communications

Amendment 1: Higher Rate, Longer Range Optical Camera Communication (OCC)

Developed by the

LAN/MAN Standards Committee
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Abstract: The existing OCC physical layer of IEEE 802.15.7-2018 is amended with one PHY specification for higher rate and longer range.

Keywords: amendment, IEEE 802.15.7, IEEE 802.15.7a, higher rate longer range, OCC, optical camera communication, physical layer

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Introduction

This introduction is not part of IEEE P802.15.7a/D8, Draft Amendment to IEEE Std 802.15.7: Higher Rate, Longer Range Optical Camera Communication

This amendment adds new transmission modes with higher rate and longer range to IEEE Std 802.15.7-2018.

It also adds mobility support, long range communication, multiple-input-multiple-output (e.g. multiple-input-multiple-output orthogonal frequency-division multiplexing (MIMO-OFDM)), and artificial intelligence (AI) -based PHY layer.

Contents

Draft Standard for Local and Metropolitan Area Networks—Part 15.7: Short-Range Optical Wireless Communications

Amendment 1: Higher Rate, Longer Range Optical Camera Communication (OCC)

NOTE—The editing instructions contained in this amendment define how to merge the material contained therein into the existing base standard and its amendments to form the comprehensive standard.

The editing instructions are shown in ***bold italic***. Four editing instructions are used: change, delete, insert, and replace. ***Change*** is used to make corrections in existing text or tables. The editing instruction specifies the location of the change and describes what is being changed by using ~~strikethrough~~ (to remove old material) and underscore (to add new material). ***Delete*** removes existing material. ***Insert*** adds new material without disturbing the existing material. Insertions may require renumbering. If so, renumbering instructions are given in the editing instruction. ***Replace*** is used to make changes in figures or equations by removing the existing figure or equation and replacing it with a new one. Editing instructions, change markings, and this NOTE will not be carried over into future editions because the changes will be incorporated into the base standard.

3. Definitions, acronyms, and abbreviations

3.2 Acronyms and abbreviations

Insert the following acronyms to the list of subclause 3.2 in alphabetical order:

BPPM	bi-level pulse position modulation
HOOK-OFDM	hybrid on-off keying orthogonal frequency division multiplexing
HS2PSK-OFDM	hybrid spatial 2-phase-shift keying orthogonal frequency division multiplexing
MIMO-COOK	multiple input multiple output camera on-off keying
MIMO-OOK	multiple input multiple output on-off keying

O-NOMA	optical non-orthogonal multiple access
RS-OFDM	rolling shutter orthogonal frequency division multiplexing
SN	sequence number

4. General description

4.4 Architecture

4.4.1 PHY types

Insert the following new list item in 4.4.1:

g) *PHY VII*: This PHY is intended for use with discrete light sources with a data rate up to 9.6 Mbps for internet of things (IoT) applications using a high-speed camera considering low mobility (<10 km/h), as defined in Table 79a.

4.4.1.1 PHY frame structure

Change the second paragraph of subclause 4.4.1.1 as indicated:

Use of over-the-air PHY frame configuration is forbidden for PHY IV, PHY V, ~~and~~ PHY VI, <u>and</u> <u>PHY VII</u>. It is mandatory that PHY frame configuration be done via the PHY PAN information base (PHY PIB). This is due to the fact that unlike traditional wireless local area networks (LANs) and personal area networks (PANs), the data rates associated with optical camera communications (OCC) are such that the configuration overhead cannot be tolerated. In other words, there is no “base default” transmission mode. In addition, it is anticipated that configuration will be with application layer “APPs” that are specifically loaded to support a particular OCC PHY mode. The PHY PIB is not transmitted; rather, it is written by the DME and is read by the PHY.

4.4.1.2 Interoperability and coexistence between PHY types

Change first paragraph of subclause 4.4.1.2 as indicated:

The PHY types coexist but do not interoperate. PHY I and PHY II occupy different spectral regions in the modulation-domain spectrum, which enables frequency division multiplexing (FDM) as a coexistence mechanism, as shown in Figure 4. PHY I and PHY III also occupy different spectral regions in the modulation-domain spectrum, with different data rates and different optical rate support, providing coexistence. However, the optical clock frequencies used for PHY II and PHY III overlap, causing significant overlap in the frequency domain spectrum. In addition, not all devices support <u>the</u> multiple optical frequency bands needed for PHY III. Hence, all PHY III devices <u>shall</u> use a PHY II ~~device for device~~ discovery <u>mode</u> to support coexistence with PHY II. PHY IV, PHY V, ~~and~~ PHY VI<u>, and PHY VII</u> are spectrally located below PHY I and use highly directive receivers (e.g., cameras) to coexist via spatial division multiplexing.

Replace Figure 4 with the following:

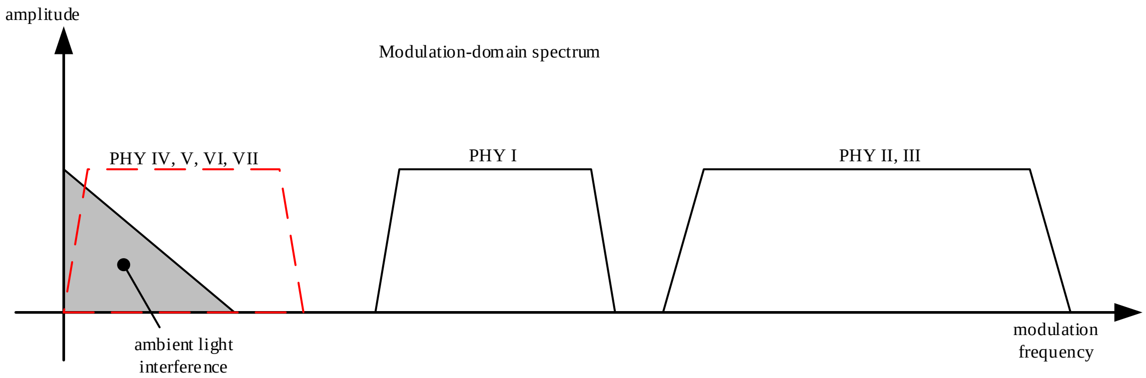


Figure 4—FDM separation of the PHY types in the modulation domain

4.8 Some media access mechanisms by PHY types

Insert the following list items in 4.8 following item "Invisible data embedding (IDE)":

— Rolling shutter orthogonal frequency division multiplexing (RS-OFDM)
— Multiple input multiple output camera on-off keying (MIMO-COOK)
— Optical non-orthogonal multiple access (O-NOMA)
— Multiple input multiple output on-off keying (MIMO-OOK)
— Hybrid on-off keying-orthogonal frequency division multiplexing (HOOK-OFDM)
— Hybrid spatial 2-phase-shift keying-orthogonal frequency division multiplexing (HS2PSK-OFDM)
— Bi-level pulse position modulation (BPPM)

5. MAC protocol specifications

5.1 MAC functional description

5.1.2 Starting an OWPAN

5.1.2.4 Device discovery

Change the title of subclause 5.1.2.4.2 and the contents as follows:

5.1.2.4.2 PHY IV, PHY V, ~~and~~ PHY VI, and PHY VII

Device types PHY IV, PHY V, ~~and~~ PHY VI, and PHY VII are not interoperable.

5.2 MAC frame formats

Change the fourth paragraph of subclause 5.2 as indicated:

Use of over-the-air MAC frame configuration shall not be done for PHY IV, PHY V, ~~and~~ PHY VI, and PHY VII, which shall accomplish MAC frame configuration via the MAC PIB. There shall be no "base default" transmission mode for PHY VI, and PHY VII. The MAC PIB shall not be transmitted; rather, it shall be written by the DME and shall be read by the MAC sublayer.

5.2.1 General MAC frame formats

5.2.1.1 Frame Control field

Insert the following new subclause 5.2.1.1.5 after subclause 5.2.1.1.4 as follows:

5.2.1.1.5 PHY VII

The frame control field shall be present when the MIMO-OOK PHY is used and shall be omitted otherwise. The MIMO-OOK Frame Control field shall be formatted as illustrated in Figure 50a.

Bits: 0-2	3	4	5	6	7
Frame type	Reserved	Security Enabled	Frame Pending	Destination OWPAN Address	Source OWPAN Address

Figure 50a—Format of the MIMO-OOK Frame Control field

a) **Frame Type subfield**. This field shall be set to one of the nonreserved values listed in Table 10a.

Table 10a—Values of the MIMO-OOK Frame Type subfield

Frame type value b2 b1 b0	Description
000	Beacon
001	Data
010	Command
011–111	Reserved

b) **Security Enable subfield**. The Security Enabled subfield shall be set to one if the frame is protected by the MAC sublayer. This subfield shall be set to zero otherwise.

c) **Frame Pending subfield**. The Frame Pending subfield shall be set to one if the device sending the frame has more data for the recipients. Otherwise, this subfield shall be set to zero. The Frame Pending subfield shall be used only with a Data frame. For synchronization frames, the Frame Pending field shall be set to zero.

d) **Destination OWPAN Address subfield**. If the Destination OWPAN Address is zero, then the Destination Address field of the generic MAC header shall not be included.

e) **Source OWPAN Address subfield**. If the Source OWPAN Address is zero, then the Source Address field of the generic MAC header shall not be included.

5.2.1.2 Sequence Number field

Insert the following new subclause 5.2.1.2.5 after subclause 5.2.1.2.4 as follows:

5.2.1.2.5 PHY VII

The Sequence Number field shall not be used except in the MIMO-OOK PHY mode.

The Sequence Number field is one octet in length and specifies the sequence identifier for the frame.

5.2.1.3 Destination OWPAN Identifier field

Delete subclauses 5.2.1.3.2 throuhg 5.2.1.3.4.

Insert the following new subclause 5.2.1.3.2 after subclause 5.2.1.3.1 as follows:

5.2.1.3.2 PHY IV, V, VI, and VII

The Destination OWPAN Identifier field shall not be used.

5.2.1.4 Destination Address field

Insert the following new subclause 5.2.1.4.5 after subclause 5.2.1.4.4 as follows:

5.2.1.4.5 PHY VII

The Destination Address field shall not be used except in the MIMO-OOK PHY mode. The Destination Address field, when present, is two octets in length and specifies the address of the intended recipient of the frame. A 16-bit value of 0xffff in this field shall represent the broadcast address, which shall be accepted as a valid 16-bit address by all devices currently listening to the channel. This field shall be included in the MAC frame only when the Destination Addressing Mode subfield of the Frame Control field is nonzero.

5.2.1.5 Source OWPAN Identifier field

Delete the current 5.2.1.5.2 through 5.2.1.5.4.

Insert the following new subclause 5.2.1.5.2 after subclause 5.2.1.5.1 as follows:

5.2.1.5.2 PHY IV, V, VI, and VII

The Source OWPAN Identifier field shall not be used.

5.2.1.6 Source Address field

Insert the following new subclause 5.2.1.6.5 after subclause 5.2.1.6.4 as follows:

5.2.1.6.5 PHY VII

The Source Address field shall not be used except in the MIMO-OOK PHY mode. The Source PAN Address, when present, is two octets in length and specifies the address of the originator of the frame. This field shall be included in the MAC frame only when the Source Addressing Mode subfield of the Frame Control field is nonzero.

5.2.1.7 Auxiliary Security Header field

Delete the current 5.2.1.7.2 through 5.2.1.7.4

Insert the following new subclause 5.2.1.7.2 after subclause 5.2.1.7.1 as follows:

5.2.1.7.2 PHY IV, V, VI, and VII

The Auxiliary Security Header field shall not be used.

5.2.1.8 Frame Payload field

Insert the following new subclause 5.2.1.8.5 after subclause 5.2.1.8.4 as follows:

5.2.1.8.5 PHY VII

The Frame Payload field shall not be used except in the MIMO-OOK PHY mode. The MPDU contains the frame payload, which has a variable length and contains information specific to individual frame types. If the frame control is configured to Security Enabled previously, then the frame payload is protected as defined by the security suite selected at that time. The bit length of the payload is specified by *macMsduLength*.

5.2.1.9 FCS field

Insert the following new subclause 5.2.1.9.5 after subclause 5.2.1.9.4 as follows:

5.2.1.9.5 PHY VII

The FCS field shall not be used except in the MIMO-OOK PHY mode. The MIMO-OOK FCS field is two octets in length, and the FCS is calculated over the MHR and MAC Payload parts of the frame. The FCS shall be generated only for payloads greater than zero bytes.

5.3 MAC command frames

5.3.19 Information element command

5.3.19.1 Capabilities information element

5.3.19.1.1 Capability Information field

Change Table 18 as indicated:

Table 18—Capability Information field

Capabilities	Bit position	Function
MAC sublayer	0	Power source
	1–2	Battery information
	3	Security capability
	4	Coordinator capability
	5	Traffic support
	6–8	Topology support
	9–10	Device type
	11	Beacon support
	12	Dimming support
	13	Continuous visibility transmission (for infrastructure)
	14	CVD support
	15–~~23~~22	Reserved
PHY	23	PHY VII support
	24	PHY I support
	25	PHY II support
	26	PHY III support
	27–28	Color stabilization capability
	29–31	Max supported TX clock
	32–34	Max supported RX clock
	35	Explicit clock notification request
	36	CCA support
	37	PHY IV support
	38	PHY V support
	39	PHY VI support

Physical device	40-42	Number of optical sources
	43-45	Multiple direction support
	46-55	Number of cells supported (n)
Band	56-63	Bands used for PHY III (any 3 bits of the bits set to 1 can be used)

Insert the following two new sentences below the sentences that read: "The PHY VI support subfield is 1 bit in length. It shall be set to 1 if the device supports PHY VI."

The PHY VII support subfield is one bit in length. It shall be set to 1 if the device supports PHY VII.

6. MAC sublayer service specification

6.4 MAC constants and PIB attributes

6.4.1 MAC constants

Change Table 61 as indicated:

Table 61—MAC sublayer constants

Constant	Description	Value
aBaseSlotDuration	The number of optical clocks forming a superframe slot when the superframe order is equal to 0 (see 5.1.1.1).	60
aBaseSuperframeDuration	The number of optical clocks forming a superframe when the superframe order is equal to 0.	*aBaseSlotDuration* × *aNumSuperframeSlots*
aExtendedAddress	The 64-bit extended address (EUI-64) assigned to the device.	Device specific
aGTSDescPersistenceTime	The number of superframes in which a GTS descriptor exists in the beacon frame of the coordinator.	4
aMaxBeaconOverhead	The maximum number of octets added by the MAC sublayer to the MAC Payload of a beacon frame.	75
aMaxBeaconPayloadLength	The maximum size, in octets, of a beacon payload.	*aMaxPHYFrameSize* – *aMaxBeaconOverhead*
aMaxLostBeacons	The number of consecutive lost beacons that will cause the MAC sublayer of a receiving device to declare a loss of synchronization.	4
aMaxMACPayloadSize	The maximum number of octets that can be transmitted in the MSDU field.	*aMaxPHYFrameSize* – *aMinMPDUOverhead*
aMaxMPDUUnsecuredOverhead	The maximum number of octets added by the MAC sublayer to the PSDU without security.	25
aMaxSIFSFrameSize	The maximum size of an MPDU, in octets, that can be followed by a SIFS period.	18
aMinCAPLength	The minimum number of optical clocks forming the CAP. This determines that MAC commands can still be transferred to devices when GTSs are being used. An exception to this minimum shall be allowed	440

	for the accommodation of the temporary increase in the beacon frame length needed to perform GTS maintenance (as defined in 5.2.2.1.3).	
aMinMPDUOverhead	The minimum number of octets added by the MAC sublayer to the PSDU.	PHY I, PHY II, and PHY III: 9 PHY IV: 0/2 PHY V and PHY VI: 7/9 PHY VII: 7/9
aNumSuperframeSlots	The number of slots contained in any superframe.	16
aUnitBackoffPeriod	The number of optical clocks forming the basic time period used by the unslotted random access algorithm.	20

8. PHY specification

8.2 Operating modes

Change first paragraph of subclause 8.2 as indicated:

A compliant PHY shall ~~be implemented~~implement at least one of the PHY I to PHY VII modes (as defined in Clause 10, Clause 11, Clause 12, Clause 13, Clause 14, ~~and~~ Clause 15, and Clause 16) given in Table 76 to Table 79a. A device implementing the PHY III mode in Table 78 shall also implement PHY II mode for coexistence as summarized in 4.4.1.2. The PHY modulation modes may operate in the presence of dimming. Modulation using OOK under dimming provides constant range and variable data rate by inserting compensation time as defined in 4.4.3.2, while modulation using VPPM under dimming provides constant data rate and variable range by adjusting the pulse width as summarized in 4.4.3.2. PHY VII mode is introduced in Clause 16 for higher rate, longer range OCC system.

Insert new Table 79a after Table 79 as follows:

Table 79a—PHY VII operating modes

OCC MCS ID	Modulation	RLL	Optical clock rate	FEC	Data rate
PHY VII operating modes					
15	RS-OFDM (4-QAM)	None	20 kHz	Hamming (8,4)	2.304 Mbps
			40 kHz	RS(15,11)	4.608 Mbps
16	RS-OFDM (16-QAM)	None	20 kHz	Hamming (8,4)	4.608 Mbps
			40 kHz	RS(15,11)	9.216 Mbps
17	MIMO-COOK	Manchester	10 kHz	Hamming (8,4)	2 Mbps
		4B6B	20 kHz	Hamming (15,11)	2.4 Mbps
		Manchester	30 kHz	Hamming (15,11)	5 Mbps
		4B6B	40 kHz	RS(15,11)	5.76 Mbps
18	O-NOMA	None	2 kHz	Hamming (8,4)	0.4 Mbps
			4 kHz	RS(15,11)	0.6 Mbps
19	MIMO-OOK	Manchester	1.5 kHz	Hamming (8,4)	8 kbps
		4B6B	2 kHz	Hamming (15,11)	9.6 kbps
		8B10B	2.5 kHz	RS (15,11)	16 kbps
20	HOOK-OFDM	Manchester for OOK	16 kHz	Hamming (8, 4) for OOK RS(15, 11) for RS-OFDM	4.8 Mbps
		4B6B for OOK	32 kHz	RS(15, 11) for OOK Hamming (8, 4) for RS-OFDM	9.6 Mbps

OCC MCS ID	Modulation	RLL	Optical clock rate	FEC	Data rate
21	HS2PSK-OFDM	Manchester for S2-PSK	16 kHz	Hamming (8, 4) for S2-PSK RS(15, 11) for RS-OFDM	3.804 Mbps
		4B6B for S2-PSK	32 kHz	RS(15, 11) for S2-PSK Hamming (8, 4) for RS-OFDM	7.68 Mbps
22	BPPM	None	10 kHz	RS(15,11) for PPM Hamming (8, 4) for AM	0.4 Mbps
			20 kHz	RS(15, 11) for PPM Hamming (8, 4) for AM	0.8 Mbps

8.3 General requirements

8.3.4 Minimum LIFS, SIFS, and RIFS periods

Change first paragraph of subclause 8.3.4 as indicated:

An interframe space (IFS) is used to provide spacing between adjacent frames. The minimum spacing between frames is dependent on the MAC mode of operation. The standard provides three types of interframe space: long (LIFS), short (SIFS), and reduced (RIFS). For peer-to-peer and star topologies, the SIFS, LIFS, and RIFS period ~~is~~ are based on the currently negotiated optical clock rate by the MAC before starting data communication. Once the optical clock rate is selected, the SIFS, LIFS, and RIFS period ~~is~~ are fixed to the values shown in Table 81. The clock-rate negotiation for a peer-to-peer and star topology is provided in 6.5. For a star topology, the beacon period and CAP are defined at the lowest optical clock rate to provide fair access to the medium. For a broadcast topology, the IFS is defined based on the optical clock rate chosen for broadcasting data to other devices. The minimum LIFS, SIFS, and RIFS periods for each of the PHYs are shown in Table 81. A detailed description, use, and illustration of LIFS, SIFS, and RIFS ~~is~~ are shown in Figure 20. Note that for PHY IV, PHY V, ~~and~~ PHY VI, and PHY VII, the variables *macMinLIFSPeriod*, *macMinSIFSPeriod*, and *macMinRIFSPeriod* are 0.

Insert one row at the end of Table 81 as indicated:

Table 81—Minimum LIFS, SIFS, and RIFS periods

PHY	*macMinLIFSPeriod*	*macMinSIFSPeriod*	*macMinRIFSPeriod*	Units
PHY I	400	120	40	Optical clocks
PHY II	400	120	40	Optical clocks
PHY III	400	120	40	Optical clocks
PHY IV	0	0	0	Optical clocks
PHY V	0	0	0	Optical clocks
PHY VI	0	0	0	Optical clocks
PHY VII	0	0	0	Optical clocks

8.5 Dimming and flicker mitigation

8.5.2 Dimming during data transmission time

Insert a new operating mode at the end of Table 83 as follows (the entire table is not shown):

Table 83—Choice of dimming methods for PHY operating modes (continued)

Mode	Compensation symbol insertion dimming	Pulse width dimming	Amplitude dimming	Out-of-band dimming
PHY VII operating modes				
RS-OFDM			x	x
MIMO-COOK			x	x
O-NOMA			x	x
MIMO-OOK			x	x
Hybrid modulation			x	x

Insert the following new subclause 8.5.2.7 after subclause 8.5.2.6 as follows:

8.5.2.7 PHY VII dimming

8.5.2.7.1 RS-OFDM

RS-OFDM dimming is achieved by controlling the amplitude of signal to the light sources.

8.5.2.7.2 MIMO-COOK

The preamble symbol and data symbols are all symmetric symbols, and the average brightness of those is constant at 50%. The optical clock rate is also constant at a considerable low frequency, 10 kHz, 20 kHz, 30 kHz, or 40 kHz.

MIMO-COOK dimming is achieved by controlling the amplitude of the ones or zeros in the OOK signal. The configuration of one level generates the average brightness output at the dimmed level (<50%). Meanwhile, the configuration of zero level achieves the average brightness output at the bright level (> 50%). The achieved dimming level is the average brightness of one and zero.

8.5.2.7.3 O-NOMA

O-NOMA dimming is achieved by controlling the amplitude of signal to the light sources.

8.5.2.7.4 MIMO-OOK

MIMO-OOK dimming is achieved by controlling the amplitude of ones or zeros in OOK signal.

8.5.2.7.5 Hybrid modulation

Hybrid modulation utilizes amplitude dimming. The BPPM implements dimming over hybrid waveforms. Two dimming levels (a low dimming level and a high dimming level) shall be applied to the high rate waveform with a higher clock rate to generate the low rate envelope of the hybrid modulation output waveform.

8.6 PPDU format

Change second paragraph in subclause 8.6 as indicated:

Use of over-the-air PHY frame configuration shall not be done for PHY IV, PHY V, ~~and~~ PHY VI, and PHY VII, which shall accomplish PHY frame configuration via the PHY PIB. There shall be no "base default" transmission mode for PHY IV, PHY V, ~~and~~ PHY VI, and PHY VII. The PHY PIB shall not be transmitted; rather, it shall be written by the DME and shall be read by the PHY.

8.6.1 Preamble field

Insert the following new subclause 8.6.1.5 after subclause 8.6.1.4 as follows:

8.6.1.5 PHY VII

8.6.1.5.1 RS-OFDM Preamble field

The Preamble field shall not be used.

8.6.1.5.2 MIMO-COOK Preamble field

The Preamble field for MIMO-COOK is an OOK signal that is configurable by PIB attribute *phyMimoCookPreamble* defined in Table 115.

8.6.1.5.3 O-NOMA Preamble field

The Preamble field shall not be used.

8.6.1.5.4 MIMO-OOK Preamble field

The Preamble field for MIMO-OOK is an OOK signal that is configurable by PIB attribute *phyMimoOokPreamble*.

8.6.1.5.5 Hybrid Modulation Preamble field

The Preamble field for Hybrid Modulation is a hybrid signal that is configurable by PIB attribute *phyLowRatePreamble* and *phyHighRatePreamble*.

8.6.2 PHY Header field

Insert the following new subclause 8.6.2.5 after subclause 8.6.2.4 as follows:

8.6.2.5 PHY VII

8.6.2.5.1 RS-OFDM Header field

The RS-OFDM PHY Header field is described in Table 92a.

Table 92a—RS-OFDM header field

PHY Header subfields	Bit width	Explanation on usage
PSDU Length	16	PSDU Length in byte
Reserved fields	6	Future use

8.6.2.5.2 MIMO-COOK Header field

The PHY Header field shall not be used.

8.6.2.5.3 O-NOMA Header field

The O-NOMA PHY Header field is described in Table 92b.

Table 92b—O-NOMA header field

PHY Header subfields	Bit width	Explanation on usage
PSDU Length	16	PSDU Length in byte
Reserved fields	6	Future use

8.6.2.5.4 MIMO-OOK Header field

The PHY Header field shall not be used.

8.6.2.5.5 Hybrid modulation Header field

The PHY Header field shall not be used.

8.6.3 HCS field

Insert the following new subclause 8.6.3.5 after subclause 8.6.3.4 as follows:

8.6.3.5 PHY VII

The HCS field shall not be used.

8.6.4 Optional field

Insert the following new subclause 8.6.4.5 after subclause 8.6.4.4 as follows:

8.6.4.5 PHY VII

The Optional field shall not be used.

8.6.5 PSDU field

Insert the following new subclause 8.6.5.5 after subclause 8.6.5.4 as follows:

8.6.5.5 PHY VII

8.6.5.5.1 RS-OFDM PSDU field

The number of payload bits in the RS-OFDM PSDU field is variable, counted from the preamble of the PPDU packet to the preamble of the next PPDU packet.

8.6.5.5.2 MIMO-COOK PSDU field

The MIMO-COOK PSDU field consists of multiple data sub-packets as seen in Figure 142a. The architecture of MIMO-COOK sub-packet is illustrated in Figure 142b. Each data sub-packet consists of its own preamble and its data sub-packet payload carrying the SN and data bits. The configuration of PSDU length is implemented via the PHY PIB attribute *phyPSDULength*.

PSDU			
Sub-packet 1	Sub-packet 2	…	Sub-packet N

Figure 142a—PSDU types for MIMO-COOK

Preamble	Data sub-packet payload			
	SN (start)	LED_ID	data bits (LED-ID)	SN (end)

Figure 142b—Sub-packet of MIMO-COOK

8.6.5.5.3 O-NOMA PSDU field

The number of payload bits in the O-NOMA PSDU field is variable, counted from the preamble of the PPDU packet to the preamble of the next PPDU packet.

8.6.5.5.4 MIMO-OOK PSDU field

The MIMO-OOK PSDU field consists of multiple data sub-packets as seen in Figure 142c. The architecture of MIMO-OOK sub-packet is illustrated in Figure 142d.

The configuration of PSDU length is implemented via the PHY PIB attribute *phyPSDULength*.

PSDU			
Sub-packet 1	Sub-packet 2	…	Sub-packet N

Figure 142c—PSDU types for MIMO-OOK

Preamble	Data sub-packet payload	
	LED_ID	data bits (LED-ID)

Figure 142d—Sub-packet of MIMO-OOK

8.6.5.5.5 Hybrid Modulation PSDU field

The Hybrid Modulation PSDU field consists of multiple low rate waveform cycle times; each cycle is a packet that has a low dimming period and a high dimming period so each period also consists of multiple high rate encoder symbols. Each symbol carries OFDM packet length bits of data. The HOOK-OFDM PSDU packet format is illustrated in Figure 142e.

Low dimming period of low rate encoder			High dimming period of low rate encoder		
High rate encoder symbol 1	…	High rate encoder symbol N	High rate encoder symbol 1	…	High rate encoder symbol N

Figure 142e—Hybrid modulation PSDU packet format

9. PHY service specifications

9.5 PHY constants and PIB attributes

9.5.2 PHY PIB attributes

Insert new rows into the end of Table 115 as follows (the entire table is not shown):

Table 115—PHY PIB attributes (continued)

Attribute	Identifier	Type	Range	Description
Part N: PHY PIB attributes for RS-OFDM mode				
phyOfdmOpticalClockRate	0x96	Integer	0-7	This attribute specifies the optical clock rate (or symbol rate) applied to RS-OFDM. 0: 20 kHz 1: 40 kHz Others: Reserved
phyOfdmMode	0x97	Integer	0-3	This attribute specifies the mode of RS-OFDM. 0: Mode 1 1: Mode 2 2: Mode 3 3: Mode 4
phyOfdmFec	0x98	Integer	0-7	This attribute specifies the FEC for RS-OFDM. 0: None 1: FEC: Hamming (8,4) 2: FEC: RS(15,11) Other values: Reserved
phyOfdmPacket	0x99	Integer	0-3	This attribute specifies the symbol length of RS-OFDM packet. 0: 64 1: 128 Other values: Reserved
phyOfdmSn	0x9a	Integer	0-3	This attribute specifies the length of sequence number per packet of RS-OFDM. 0: 2 bits 1: 3 bits Other values: reserved
phyOfdmQam	0x9b	Integer	0-7	This attribute specifies the QAM level of RS-OFDM. 0: 4-QAM 1: 16-QAM Other values: reserved
Part O: PHY PIB attributes for MIMO-COOK mode				
phyMimoCookOpticalClockRate	0x9c	Integer	0-7	This attribute specifies the optical clock rate (or symbol rate) applied to MIMO-COOK. 0: 10 kHz 1: 20 kHz 2: 30 kHz 3: 40 kHz Others: Reserved
phyMimoCookRLLCode	0x9d	Integer	0-7	This attribute specifies the RLL coding for MIMO-COOK. 0: Manchester 1: 4B6B Other values: Reserved
phyMimoCookFec	0x9e	Integer	0-7	This attribute specifies the FEC for MIMO-COOK. modulation. 0: None 1: Hamming (8,4) 2: Hamming (15,11) 3: RS (15,11) Other values: Reserved

Attribute	Identifier	Type	Range	Description
phyMimoCookPreamble	0x9f	Integer	0-3	This attribute specifies the preamble symbol of PSDU of MIMO-COOK. 0: 6B symbol (preamble = 011100) 1: 10B symbol (preamble = 0011111000) Other values: Reserved
phyMimoCookSn	0xa0	Integer	0-3	This attribute specifies the length of sequence number per packet of MIMO-COOK. 0: 2 bits 1: 3 bits Other values: reserved
phyMimoCookLedId	0xa1	Integer	0-3	This attribute specifies the length of LED-ID data for MIMO-COOK. 0: 2 bits 1: 3 bits Other values: Reserved
phyMimoCookMode	0xa2	Integer	0-3	This attribute specifies the mode of MIMO-COOK. 0: Mode 1 1: Mode 2 2: Mode 3 3: Mode 4
phyMimoCookNumberLED	0xa3	Integer	0-3	This attribute specifies the number of LED in MIMO-COOK. 0: 2 1: 4 Others: Reserved
phyMimoCookSubPacketLength	0xa4	Integer	0-3	This attribute specifies the data sub-packet length of MIMO-COOK. 0: 100 bits 1: 120 bits 2: 200 bits 3: 240 bits
Part P: PHY PIB attributes for O-NOMA mode				
phyNomaOpticalClockRate	0xa5	Integer	0-7	This attribute specifies the optical clock rate (or symbol rate) applied to O-NOMA. 0: 2 kHz 1: 4 kHz Others: Reserved
phyNomaPowerLevel	0xa6	Integer	0-7	This attribute specifies the number of power levels for O-NOMA. 0: 2 1: 3 Other values: Reserved
phyNomaFec	0xa7	Integer	0-7	This attribute specifies the FEC for O-NOMA. 0: None 1: Hamming (8,4) 2: RS (15,11) Other values: Reserved
phyNomaMode	0xa8	Integer	0-7	This attribute specifies the mode of O-NOMA. 0: Mode 1 1: Mode 2 Others: Reserved
phyNomaPacketLength	0xa9	Integer	0-7	This attribute specifies the data packet length of O-NOMA. 0: 100 bits

Attribute	Identifier	Type	Range	Description
				1: 150 bits Other values: Reserved
Part Q: PHY PIB attributes for MIMO-OOK mode				
phyMimoOokOpticalClockRate	0xaa	Integer	0-7	This attribute specifies the optical clock rate (or symbol rate) applied to MIMO-OOK. 0: 1.5 kHz 1: 2 kHz 2: 2.5 kHz Others: Reserved
phyMimoOokRLLCode	0xab	Integer	0-7	This attribute specifies the RLL coding for MIMO-OOK. 0: Manchester 1: 4B6B 2: 8B10B Other values: Reserved
phyMimoOokFec	0xac	Integer	0-7	This attribute specifies the FEC for MIMO-OOK. 0: None 1: CC(1,4) as inner FEC; Hamming (8,4) as outer FEC 2: CC(1,3) as inner FEC; RS(15,11) as outer FEC 3: CC(1,4) as inner FEC; RS(15,7) as outer FEC Other values: Reserved
phyMimoOokPreamble	0xad	Integer	0-7	This attribute specifies the preamble symbol of PSDU for MIMO-OOK. 0: 6B symbol (preamble = 011100) 1: 10B symbol (preamble = 0011111000) 2: 14B symbol (preamble=00011111110000) Other values: Reserved
phyMimoOokNumberLED	0xae	Integer	0-3	This attribute specifies the number of LED in MIMO-OOK. 0: 2 1: 3 Others: Reserved
phyMimoOokLedId	0xaf	Integer	0-3	This attribute specifies the length of LED-ID data for MIMO-OOK. 0: 2 bits 1: 3 bits Other values: Reserved
phyMimoOokMode	0xb0	Integer	0-7	This attribute specifies the mode of MIMO-OOK. 0: Mode 1 1: Mode 2 2: Mode 3 Others: Reserved
phyMimoOokSubPacketLength	0xb1	Integer	0-7	This attribute specifies the data sub-packet length of MIMO-OOK. 0: 20 bits 1: 24 bits 2: 40 bits Other values: Reserved
Part R: PHY PIB attributes for Hybrid Modulation				
phyHybridModulationMode	0xb2	Integer	0-7	This attribute specifies the mode of hybrid modulation. 0: HOOK-OFDM

Attribute	Identifier	Type	Range	Description
				1: HS2PSK-OFDM 2: BPPM Others: Reserved
phyLowRatePreamble	0xb3	Integer	0-3	This attribute specifies the preamble symbol of PSDU for low rate encoder in hybrid modulation. 0: 6B symbol (preamble = 011100) 1: 10B symbol (preamble = 0011111000)
phyHighRatePreamble	0xb4	Integer	0-3	This attribute specifies the preamble symbol of PSDU for high rate encoder in hybrid modulation. 0: 8B symbol (preamble = 01111100) 1: 12B symbol (preamble=001111111000) Other values: Reserved
phyLowRateFec	0xb5	Integer	0-3	This attribute specifies the FEC for low rate encoder in hybrid modulation. 0: None 1: Hamming (8,4) 2: RS (15,11) Other values: Reserved
phyHighRateFec	0xb6	Integer	0-3	This attribute specifies the FEC for high rate encoder in hybrid modulation. 0: None 1: Hamming (8,4) 2: RS (15,11) Other values: Reserved
phyHybridModulationClk	0xb7	Integer	0-7	This attribute specifies the optical clock rate (or symbol rate) applied to hybrid modulation. 0: 10 kHz 1: 16 kHz 2: 20 kHz 3: 32 kHz Other values: Reserved
phyHybridModulationRLLCode	0xb8	Integer	0-7	This attribute specifies the RLL coding for hybrid modulation. 0: Manchester 1: 4B6B Other values: Reserved

Insert the following new Clause 16 after Clause 15:

16. PHY VII specifications

16.1 Rolling shutter orthogonal frequency division multiplexing (RS-OFDM)

RS-OFDM is the concept of using a electronic shutter to capture the OFDM signal in sequential snapshots. The RS-OFDM data rates and operating conditions are shown in PHY VII operating modes (see Table 79a).

16.1.1 Reference architecture

A reference architecture to implement RS-OFDM is shown in Figure 216a.

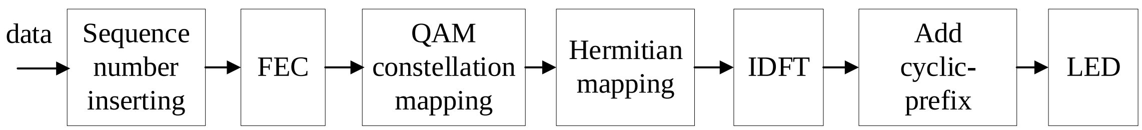


Figure 216a—Rolling Shutter OFDM block diagram

16.1.2 Data packet structure

The RS-OFDM data packet structure is illustrated in Figure 216b. A data sub-packet shall consist of two subfields: a sequence number part and a payload part. The RS-OFDM data packet length shall be configured via the PHY PIB attribute *phyOfdmPacket*.

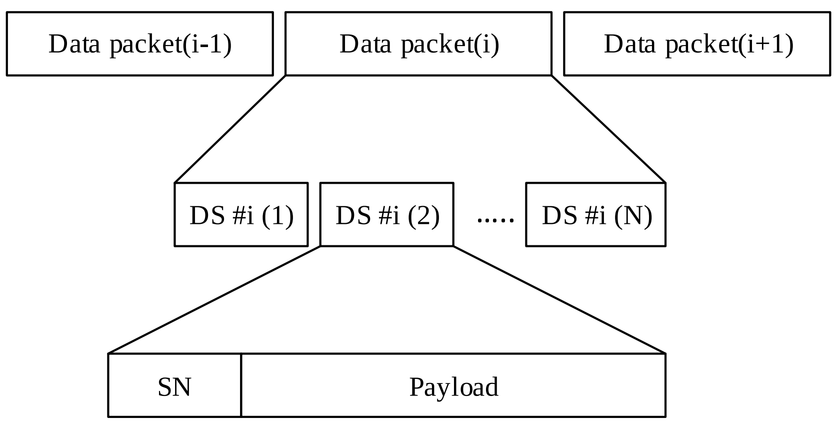


Figure 216b—RS-OFDM data packet structure

16.1.3 Sequence number inserting

The data sub-packet payload shall consist of two subparts: SN data and payload. The SN data consists of asynchronous information, which helps the receiver side decode data. SN shall be implemented over the PHY PIB attribute *phyOfdmSn*.

16.1.4 Forward error correction (FEC)

The data sub-packet payload shall be coded by FEC to protect the payload from error. Hamming (8,4) or Reed Solomon (15,11) code may be used as an FEC. FEC shall be configured via the PHY PIB attribute *phyOfdmFec*.

16.1.5 QAM constellation mapping

4-QAM and 16-QAM shall be used in RS-OFDM modulation scheme. The QAM level shall be configured via the PHY PIB attribute *phyOfdmQam*.

16.1.6 Hermitian mapping

Unlike the conventional OFDM in RF, instead of feeding the data symbol directly into the IDFT block, each symbol must pass through the Hermitian block. The signal is then fed into the IFFT. The special purpose of the Hermitian block is that it ensures the output of the IDFT is entirely real.

The following equation illustrates the Hermitian mapping process:

$$X_m = X^*_{N-m} \text{ for } 0 < m < N \text{ and } X_0, X_1, X_2.....X_{N-1}$$
$$X = [0, X_1, X_2....0....X^*_2, X^*_1]$$

16.1.7 Summary of RS-OFDM PHY mode parameters

Table 151a describes the summary of RS-OFDM PHY mode parameters depending on the supported mode. The RS-OFDM PHY mode parameters shall be configured via the PHY PIB attribute *phyOfdmMode*. And the RS-OFDM data packet length shall be configured via the PHY PIB attribute *phyOfdmPacket*. The optical clock rate is at 20 kHz or 40 kHz. The optical clock rate at which RS-OFDM symbols are clocked out is configurable over PHY PIB attribute *phyOfdmOpticalClockRate*.

Table 151a— RS-OFDM PHY mode parameters

	Mode 1	**Mode 2**	**Mode 3**	**Mode 4**
Optical clock rate	20 kHz	40 kHz	20 kHz	40 kHz
RS-OFDM data packet length	64 bits	128 bits	64 bits	128 bits
FEC	Hamming (8,4)	RS (15,11)	Hamming (8,4)	RS (15,11)
QAM level	4-QAM	4-QAM	16-QAM	16-QAM
Data rate	2.304 Mbps	4.608 Mbps	4.608 Mbps	9.216 Mbps

16.2 Multiple input multiple output camera on-off keying (MIMO-COOK)

MIMO-COOK is the concept of using a electronic shutter to capture the OOK signal in sequential snapshots. The MIMO-COOK data rates and operating conditions are shown in PHY VII operating modes (see Table 79a).

16.2.1 Reference architecture

A reference architecture to implement MIMO-COOK is shown in Figure 216c.

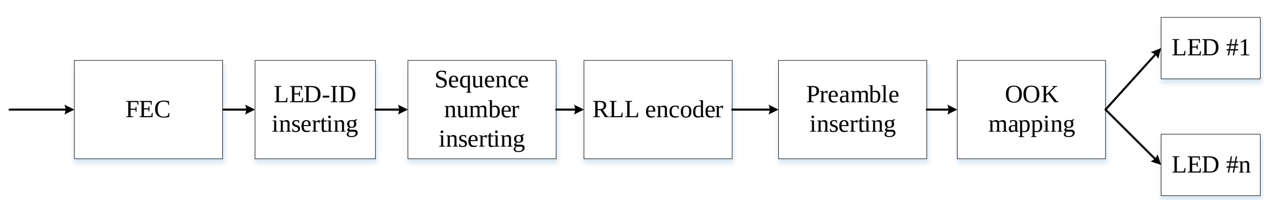


Figure 216c—MIMO-COOK block diagram

16.2.2 Data packet structure

The data packet structure is shown in Figure 216d. A data sub-packet shall consist of four subfields: LED-ID part, a sequence number part, a forward payload, and a backward payload part. A packet consists of multiple similar data sub-packets to avoid missing data between adjacent images. The number of repetitions depends on the communication mode specified later. The data sub-packet format of MIMO-COOK is illustrated in Figure 216e. The data sub-packet length of MIMO-COOK shall be configured via the PHY PIB attribute *phyMimoCookSubPacketLength*.

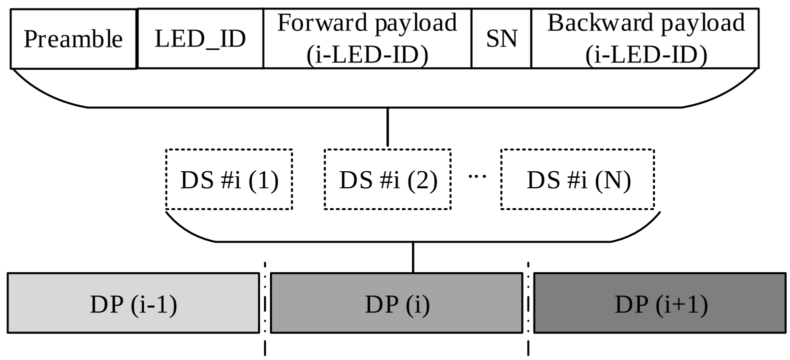


Figure 216d—MIMO-COOK data packet structure

Preamble (bits)	Data sub-packet payload			
	LED-ID	Forward payload	SN	Backward payload
011100	Manchester coding			
0011111000	4B6B coding			

Figure 216e—Data sub-packet format of MIMO-COOK

16.2.3 Forward error correction (FEC)

The data sub-packet payload shall be coded by FEC to protect the payload from error. Hamming (8,4), Hamming (15, 11), or Reed Solomon (15,11) code may be used as an FEC. FEC shall be configured via the PHY PIB attribute *phyMimoCookFec*.

16.2.4 Sequence number inserting

The data sub-packet payload shall consist of two subparts: SN data and payload. The SN data consists of asynchronous information, which helps the receiver side decode data. SN shall be implemented over the PHY PIB attribute *phyMimoCookSn*.

16.2.5 RLL coding

RLL coding shall be applied in the payload subfield to maintain an average brightness off 50%. Manchester code and 4B6B code are suggested for OOK mode. The configuration of RLL code shall be implemented over the PHY PIB attribute *phyMimoCookRLLCode*. Manchester code or 4B6B code is suggested for MIMO-COOK mode.

16.2.6 Preamble

The preamble part shall carry the same information in each Data sub-packet, which consists of the special information to recognize the start of packet as shown in Figure 216e and Table 151b. The configuration of preamble shall be implemented over the PHY PIB attribute *phyMimoCookPreamble*.

16.2.7 Summary of MIMO-COOK PHY mode parameters

Table 151b describes the summary of MIMO-COOK PHY mode parameters depending on the supported mode. The MIMO-COOK PHY mode parameters shall be configured via the PHY PIB attribute *phyMimoCookMode*. A packet of data is modulated using OOK modulation. The optical clock rate is at 10 kHz, 20 kHz, 30 kHz, or 40 kHz. The optical clock rate at which MIMO-COOK symbols are clocked out is configurable over the PHY PIB attribute *phyMimoCookOpticalClockRate*. The configuration of number of LEDs shall be implemented over the PHY PIB attribute *phyMimoCookNumberLED*.

Table 151b—MIMO-COOK PHY mode parameters

	Mode 1	Mode 2	Mode 3	Mode 4
Optical clock rate	10 kHz	20 kHz	30 kHz	40 kHz
Data sub-packet length	100 bits	120 bits	200 bits	240 bits
Preamble	6 bits	10 bits	6 bits	10 bits
RLL code	Manchester	4B6B	Manchester	4B6B
Number of LEDs	2	2	4	4
FEC	Hamming (8,4)	Hamming (15,11)	Hamming (15,11)	RS (15,11)
Data rate	2 Mbps	2.4 Mbps	5 Mbps	5.76 Mbps

16.3 Optical non-orthogonal multiple access (O-NOMA)

O-NOMA is the concept of using a electronic shutter to capture the NOMA signal in sequential snapshots. The O-NOMA data rates and operating conditions are shown in PHY VII operating modes (see Table 79a).

16.3.1 Reference architecture

A reference architecture to implement O-NOMA is shown in Figure 216f.

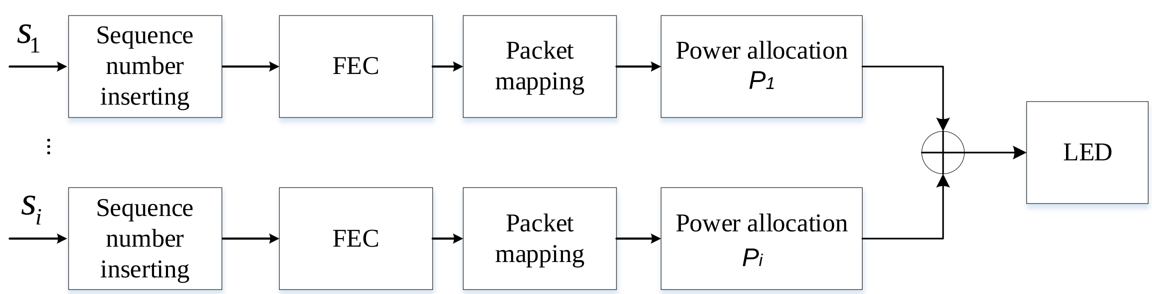


Figure 216f—O-NOMA block diagram

16.3.2 Data packet structure

The O-NOMA data packet structure is illustrated in Figure 216g. A data packet shall consist of two subfields: a sequence number part and a payload part. O-NOMA data packet length shall be configured via the PHY PIB attribute *phyNomaPacketLength*.

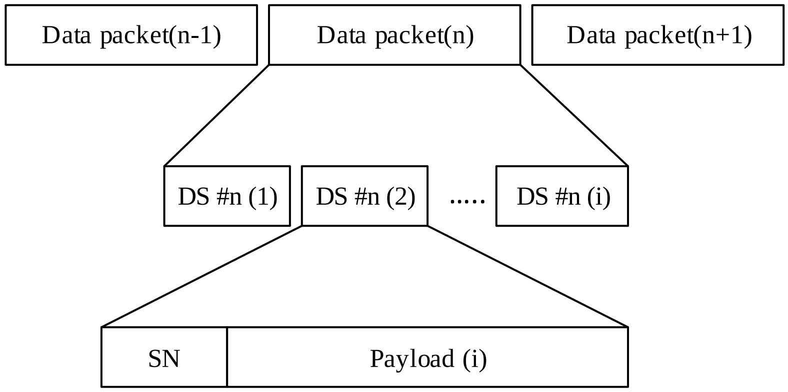


Figure 216g—O-NOMA data packet structure

16.3.3 Forward error correction (FEC)

The data packet payload shall be coded by FEC to protect the payload from error. Hamming (8,4) or Reed Solomon (15,11) code shall be used as an FEC. FEC shall be configured via the PHY PIB attribute *phyNomaFec*.

16.3.4 Power allocation

The number of power levels of O-NOMA scheme shall be configurable over the PHY PIB attribute *phyNomaPowerLevel*. The number of power levels represents the data encoding scheme with n-stage power allocation. Figure 216h shows the data encoding scheme with 2-stage power allocation using O-NOMA system. The data packet length of O-NOMA shall be configured via the PHY PIB attribute *phyNomaPacketLength*.

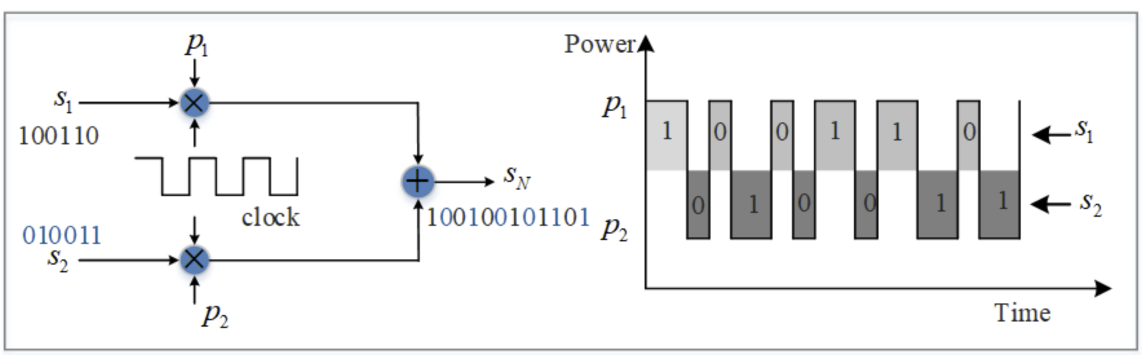


Figure 216h—Data encoding scheme of 2-stage power allocation based O-NOMA system

16.3.5 Summary of O-NOMA PHY mode parameters

Table 151c describes the summary of O-NOMA PHY mode parameters depending on the supported mode. The O-NOMA PHY mode parameters shall be configured via the PHY PIB attribute *phyNomaMode*. A packet of data is modulated using O-NOMA modulation. The optical clock rate is at 2 kHz or 4 kHz. The optical clock rate at which O-NOMA symbols are clocked out is configurable over PHY PIB attribute *phyNomaOpticalClockRate*.

Table 151c—O-NOMA PHY mode parameters

	Mode 1	Mode 2
Optical clock rate	2 kHz	4 kHz
Power levels	2	3
Data packet length	100 bits	150 bits
FEC	Hamming (8,4)	RS (15,11)
Data rate	0.4 Mbps	0.6 Mbps

16.4 Multiple input multiple output on-off keying (MIMO-OOK)

MIMO-OOK is the concept of using a frame rate to capture the OOK signal in sequential snapshots. The MIMO-OOK data rates and operating conditions are shown in PHY VII operating modes (see Table 79a).

16.4.1 Reference architecture

A reference architecture to implement MIMO-OOK is shown in Figure 216i.

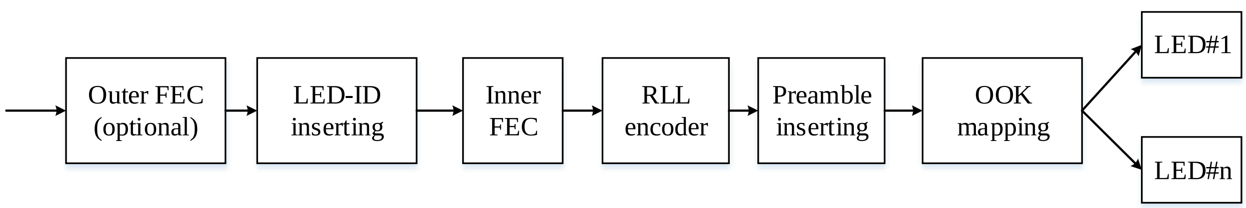
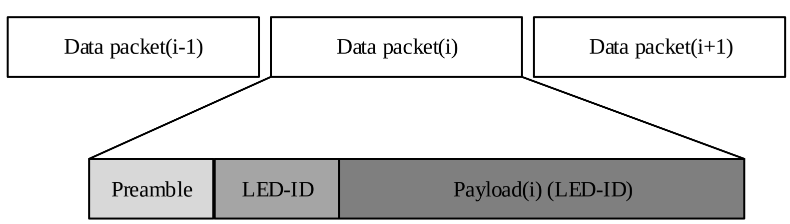


Figure 216i—MIMO-OOK block diagram

16.4.2 Data packet structure

The data packet structure is illustrated in Figure 216j. The clock rate of the MIMO-OOK scheme was set up lower than (at least two times) the camera frame rate to eliminate the variation effect of frame rate. Data sub-packet length of MIMO-OOK shall be configured via the PHY PIB attribute *phyMimoOokSubPacketLength*.



LED-ID: LED identification

Figure 216j—MIMO-OOK data packet structure

To access multiple light sources, the LED-ID is inserted in each packet. The data sub-packet format of MIMO-OOK is illustrated in Figure 216k.

Preamble (bits)	Data sub-packet payload	
	LED-ID	Payload
011100	Manchester coding	
0011111000	4B6B coding	
00011111110000	8B10B coding	

Figure 216k—Data sub-packet format of MIMO-OOK

16.4.3 Forward error correction (FEC)

The data sub-packet payload shall be coded by the inner FEC to protect the payload from error. CC (1,4) or CC(1,3) code may be used as an inner FEC.

Additionally, the outer FEC may also be used to protect the PHR and PSDU. When outer FEC is enabled, Hamming (8,4), RS(15,11), and RS(15,7) shall be implemented. Inner FEC and outer FEC shall be configured via the PHY PIB attribute *phyMimoOokFec.*

16.4.4 LED-ID inserting

To access multiple light sources, the LED-ID is inserted in each packet. The data sub-packet format of MIMO-OOK is illustrated in Figure 216j. The length of LED-ID shall be implemented over the PHY PIB attribute *phyMimoOokLedId.*

16.4.5 RLL coding

RLL coding shall be applied in the payload subfield to maintain an average brightness at 50%. Manchester code and 4B6B code are suggested for MIMO-OOK mode. The configuration of RLL code shall be implemented over the PHY PIB attribute *phyMimoOokRLLCode*.

16.4.6 Preamble

The preamble part shall carry the same information in each sub-data packet, which consists of the special information to recognize the start of packet. The preamble shall be implemented over the PHY PIB attribute *phyMimoOokPreamble.*

16.4.7 Summary of MIMO-OOK PHY mode parameters

Table 151d describes the summary of MIMO-OOK PHY mode parameters depending on the supported mode. The MIMO-OOK PHY mode parameters shall be configured via the PHY PIB attribute *phyMimoOokMode*. A packet of data is modulated using OOK modulation. The optical clock rate is at 1.5 kHz, 2 kHz, or 2.5 Hz. The optical clock rate at which MIMO-OOK symbols are clocked out is configurable over PHY PIB attribute *phyMimoOokOpticalClockRate*.

Table 151d—MIMO-OOK PHY mode parameters

	Mode 1	Mode 2	Mode 3
Optical clock rate	1.5 kHz	2 kHz	2.5 kHz
Data sub-packet length	20 bits	24 bits	40 bits
Preamble	6 bits	10 bits	14 bits

RLL code	Manchester	4B6B	8B10B
Number of LEDs	2	3	2
Outer FEC	Hamming (8,4)	RS (15,11)	RS (15, 7)
Inner FEC	CC (1,4)	CC (1,3)	CC (1,4)
Data rate	8 kbps	9.6 kbps	16 kbps

16.5 Hybrid modulation

16.5.1 Reference architecture

A reference architecture of hybrid modulation is shown in Figure 216l.

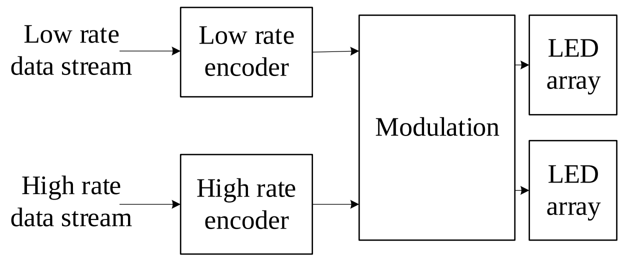


Figure 216l—Hybrid modulation block diagram

16.5.2 Data packet structure

The configuration of the mode of the hybrid modulation scheme shall be implemented via the PHY PIB attribute *phyHybridModulationMode*. In each 'high' and 'low' period of the low rate encoder waveform, the high rate encoder waveform is embedded to increase the data rate of the system. The data packet structure of hybrid modulation scheme is described in Figure 216m.

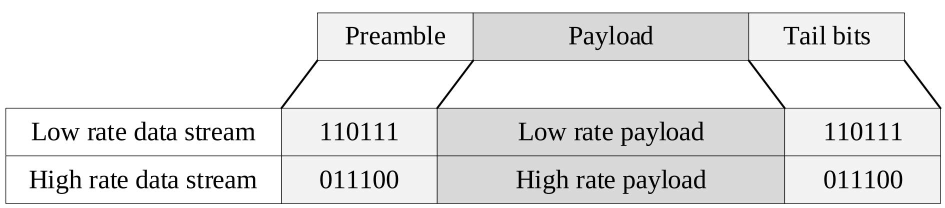


Figure 216m- Data packet structure of hybrid modulation scheme

16.5.3 Examples of hybrid OCC system

16.5.3.1 Hybrid on-off keying orthogonal frequency division multiplexing (HOOK-OFDM)

HOOK-OFDM is the concept of using a electronic shutter to capture the OOK and the OFDM signals in sequential snapshots. The HOOK-OFDM data rates and operating conditions are shown in PHY VII operating modes (see Table 79a).

A reference architecture of HOOK-OFDM is shown in Figure 216n. The optical clock rate is 16 kHz or 32 kHz. In each 'high' and 'low' period of C-OOK waveform, OFDM waveform is embedded to increase data rate of the system. The configuration of the optical clock rate of HOOK-OFDM scheme shall be implemented via the PHY PIB attribute *phyHybridModulationClk.*

RLL coding shall be applied in the payload subfield to maintain an average brightness of 50%. Manchester code and 4B6B code are suggested for the low rate data stream (OOK modulation). The configuration of RLL code shall be implemented over the PHY PIB attribute *phyHybridModulationRLLCode.*

The preamble part shall carry the same information in each packet, which consists of the special information to recognize the start of packet as shown in Figure 216n and Table 151e. The configuration of the preambles of high rate stream and low rate stream shall be implemented over the PHY PIB attribute *phyHighRatePreamble and phyLowRatePreamble.* The configuration of FEC shall be implemented over the PHY PIB attribute *phyLowRateFec* and *phyHighRateFec.*

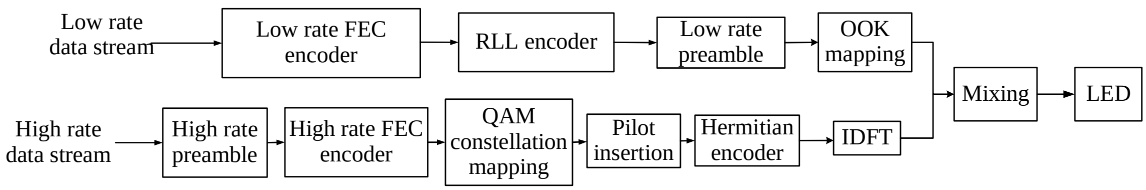


Figure 216n—HOOK-OFDM block diagram

Table 151e describes the summary of HOOK-OFDM PHY mode parameters depending on the supported mode.

Table 151e—HOOK-OFDM PHY mode parameters

	Mode 1	**Mode 2**
Optical clock rate	16 kHz	32 kHz
Symbol length	64 bits (4 QAM-OFDM) 12 bits (OOK)	128 bits (16 QAM-OFDM) 24 bits (OOK)
RLL code	Manchester	4B6B
Preamble	6 bits (low rate data stream) 8 bits (high rate data stream)	10 bits (low rate data stream) 12 bits (high rate data stream)
FEC	Hamming (8,4) (low rate data stream) RS (15,11) (high rate data stream)	RS (15,11) (low rate data stream) Hamming (8,4) (high rate data stream)
Bit rate	4.8 Mbps	9.6 Mbps

16.5.3.2 Hybrid spatial 2-phase-shift keying orthogonal frequency division multiplexing (HS2PSK-OFDM)

HS2PSK-OFDM is the concept of using a electronic shutter to capture the OFDM signal and a frame rate to capture S2-PSK signal. The HS2PSK-OFDM data rates and operating conditions are shown in PHY VII operating modes (see Table 79a).

A reference architecture to implement HS2PSK-OFDM is shown in Figure 216o. The optical clock rate is at 16 kHz or 32 kHz. In each ‘high’ and ‘low’ period of S2-PSK waveform, OFDM waveform is embedded to increase data rate of the system. The configuration of the optical clock rate of HS2PSK-OFDM scheme shall be implemented via the PHY PIB attribute *phyHybridModulationClk.*

RLL coding shall be applied in the payload subfield to maintain an average brightness of 50%. Manchester code and 4B6B code are suggested for the low rate data stream (S2-PSK modulation). The configuration of RLL code shall be implemented over the PHY PIB attribute *phyHybridModulationRLLCode.*

The preamble part shall carry the same information in each packet, which consists of special information to recognize the start of packet as shown in Figure 216o and Table 151f. The configuration of the preambles for high rate stream and low rate stream shall be implemented over the PHY PIB attribute *phyHighRatePreamble and phyLowRatePreamble*. The configuration of FEC shall be implemented over the PHY PIB attribute *phyLowRateFec* and *phyHighRateFec*.

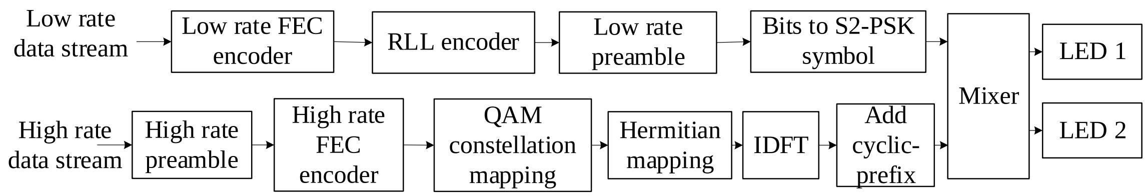


Figure 216o—HS2PSK-OFDM block diagram

Table 151f describes the summary of HS2PSK-OFDM PHY mode parameters depending on the supported mode.

Table 151f—HS2PSK-OFDM PHY mode parameters

	Mode 1	Mode 2
Optical clock rate	16 kHz	32 kHz
Symbol length	64 bits (4 QAM-OFDM) 12 bits (S2-PSK)	128 bits (16 QAM-OFDM) 24 bits (S2-PSK)
Preamble	6 bits (low rate data stream) 8 bits (high rate data stream)	10 bits (low rate data stream) 12 bits (high rate data stream)
RLL code	Manchester	4B6B
FEC	Hamming (8,4) (low rate data stream) RS (15,11) (high rate data stream)	RS (15,11) (low rate data stream) Hamming (8,4) (high rate data stream)
Bit rate	3.804 Mbps	7.680 Mbps

16.5.3.3 Bi-level pulse position modulation (BPPM)

BPPM is the concept of using a electronic shutter to capture the PPM and the AM signals in sequential snapshots. The BPPM data rates and operating conditions are shown in PHY VII operating modes (see Table 79a).

High rate data streams are modulated with a PPM scheme, and low rate data streams are modulated by an AM scheme at two different intensity levels. The PPM encoder makes every pulse in the carrier pulse sequence change with time without changing the shape and amplitude of the pulse signal. AM encoder is a process by which the wave signal is transmitted by modulating the amplitude of the signal. In AM, the voltage or power level of the information signal changes the amplitude of the carrier in proportion.

The reference architecture of BPPM is shown in Figure 216p. Each of the rear LEDs transmits the same information concurrently. High rate data streams are modulated with a PPM scheme and low rate data streams are transmitted by AM scheme at two different intensity levels. The configuration of the optical clock rate of BPPM scheme shall be implemented via the PHY PIB attribute *phyHybridModulationClk*. The configuration of FEC shall be implemented over the PHY PIB attribute *phyLowRateFec* and *phyHighRateFec*.

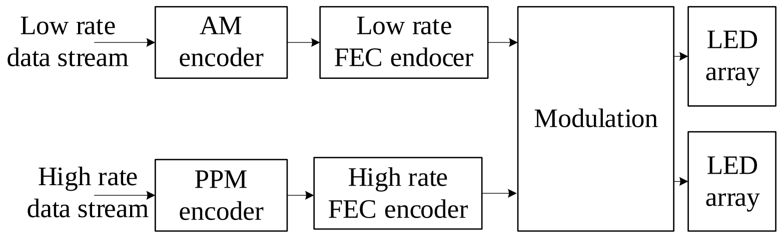


Figure 216p—Block diagram of BPPM transmitter

Table 151g describes the summary of BPPM PHY mode parameters depending on the supported mode.

Table 151g—BPPM PHY mode parameters

	Mode 1	**Mode 2**
Optical clock rate	10 kHz	20 kHz
Data sub-packet length	25 bits (low rate data stream) 100 bits (high rate data stream)	50 bits (low rate data stream) 200 bits (high rate data stream)
Preamble	6 bits (low rate data stream) 8 bits (high rate data stream)	10 bits (low data stream) 12 bits (high rate data stream)
FEC	Hamming (8,4) (low rate data stream) RS (15,11) (high rate data stream)	RS (15,11) (low rate data stream) Hamming (8,4) (high rate data stream)
Data rate	0.4 Mbps	0.8 Mbps

16.5.4 Forward error correction (FEC)

The data sub-packet payload shall be coded by FEC to protect the payload from error. The configuration of error correction for the Hibrid modulation scheme, including FEC for the low rate encoder scheme and FEC for the high rate encoder scheme, shall be implemented via the PHY PIB attribute *phyLowRateFec* and *phyHighRateFec*.

Insert the following new Annexes O and P after Annex N:

Annex O

(informative)

PHY VII Waveforms decoding guide

O.1 RS-OFDM decoding method

O.1.1 Overview

Figure O.1 illustrates the architecture of RS-OFDM decoder. Due to the frame rate variation effect from cameras, two case of decoding will be considered: Oversampling and Undersampling.

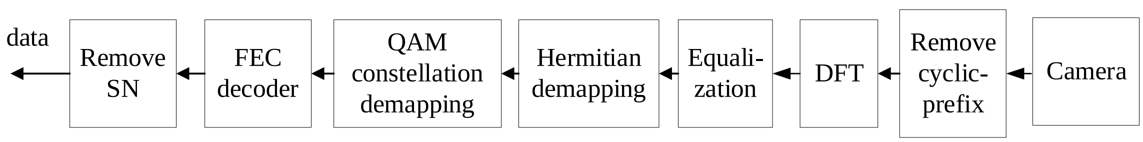


Figure O.1—RS-OFDM decoder architecture

O.1.2 Decoding case 1: Oversampling

The Oversampling is caused by the frame rate variation of the rolling shutter camera when the frame rate of a rolling-shutter camera becomes many times greater (at least double) than the packet rate of the transmitter; every data packet is sampled at least twice (i.e., two images). At the receiver, camera receive the same packet causing confusion about packet merger. To assist the receiver in reducing the effect of the frame rate variation of the camera, the SN is added to DS. Each packet contains DSs with the same SN, which helps the receiver remove redundant data. When the receiver receives a DS, it will choose which has a compatible SN. The receiver will eliminate consecutive packets with the same SN and choose packets with consecutive SN (n–1, n, n+1) for the merger as shown in Figure O.2.

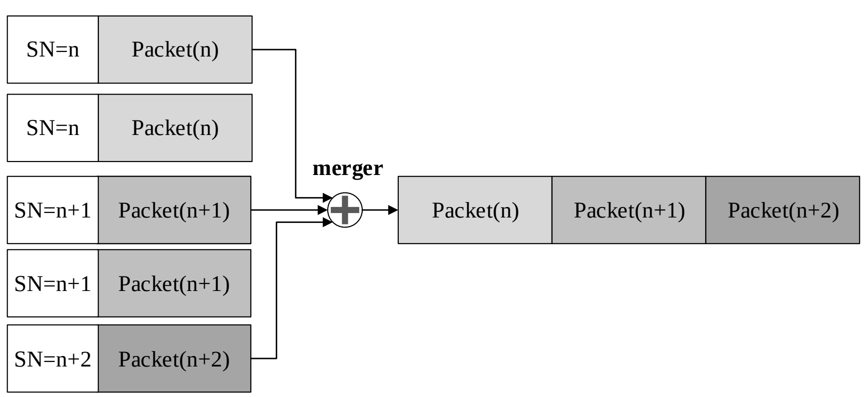


Figure O.2—Merging packet method in oversampling case

O.1.3 Decoding case 2: Undersampling

Undersampling occurs if the frame rate drops to below the packet rate of the transmitter. In this case, the payload will be lost. The detection of a missed payload using the SN is shown in Figure O.3. If the SN length is long enough, the missed payload can be detected by SN. The data packet achieved from the payload *n–1* represents the SN as *n–1*. The next data packet indicates that the SN is *n*, but the actual data packet carries SN *n+1*. This demonstrates that the payload n is missed and the loss is detected by comparing the SN of the two adjacent data sub-packets. However, depending on the length of the SN, several different states are generated. For example, if the SN length is 3 bits, seven missing payloads of transmitted packets can be detected by the SN. The error can be defined easily if SN values are not sequenced. If two consecutive packets have two non-consecutive SN (*n-1* and *n+1*), respectively.

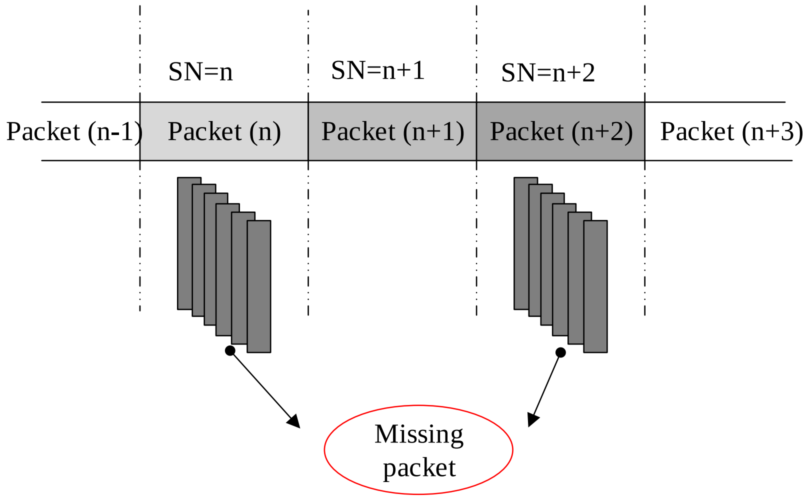


Figure O.3—Detecting missed packets in undersampling case

O.2 MIMO-COOK decoding method

O.2.1 Overview

Figure O.4 illustrates MIMO-COOK decoder architecture. Due to the frame rate variation effect from cameras, two case of decoding will be considered: Oversampling and Undersampling. Besides that, the matched filter decoder also proposed.

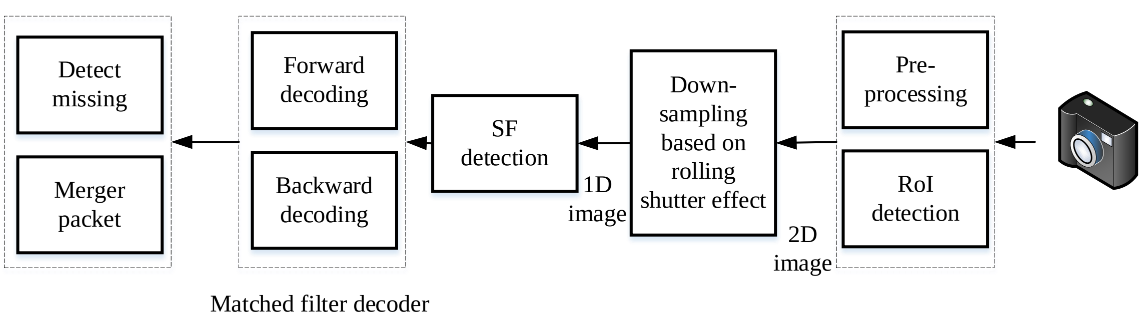


Figure O.4—MIMO-COOK decoder architecture

O.2.2 Decoding case 1: Oversampling

When the frame rate of a rolling shutter camera is at least two times larger than the packet rate of the transmitter, the data packet is sampled multiple times causing the oversampling effect. When the packet is sampled more than once, errors of packet merger are created at the receiver's end. The SN is added to the DS to deal with this problem because it improves the receiver's ability to decrease the effect of the frame rate variation of the camera. The redundant data will be removed in the receiver when the same SN value is recognized in the DS of different packets. The receiver will eliminate consecutive packets with the same SN and choose packets with consecutive SN values (n − 1, n, n + 1) for the merger as shown in Figure O.5, Figure O.6, and Figure O.7.

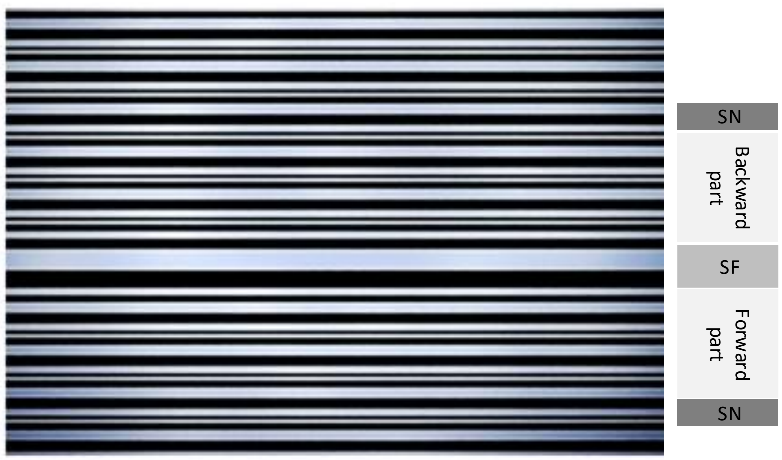


Figure O.5—Merge forward and backward parts in each image (One SF in each image)

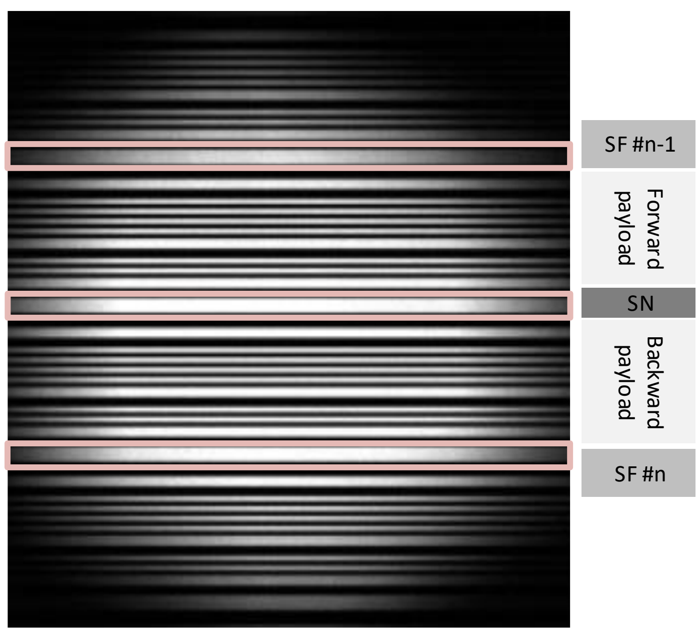


Figure O.6—Full payload in each image (Multiple SF in each image)

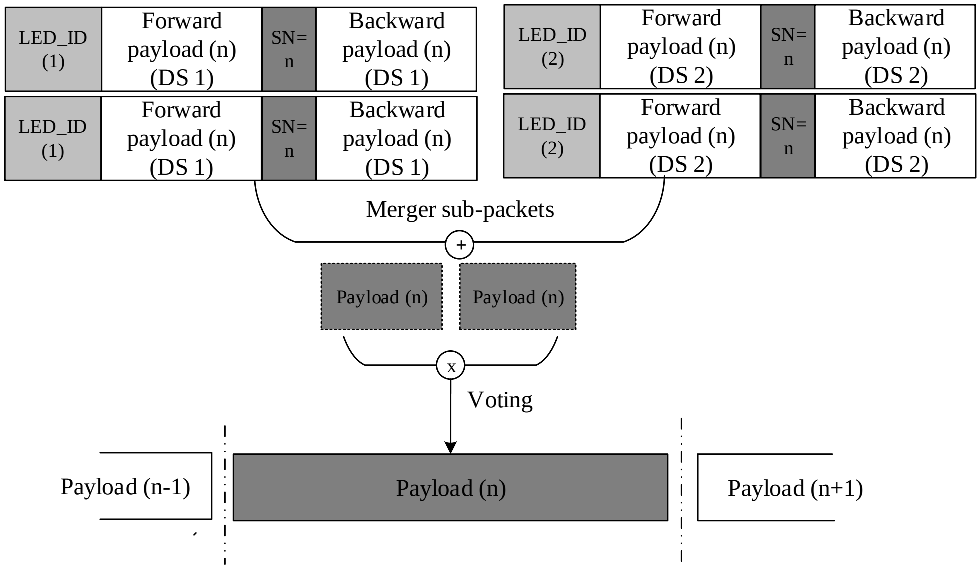


Figure O.7—Merging packet of MIMO-COOK scheme in multiple images

O.2.3 Decoding case 2: Undersampling

When the frame rate decreases below the packet rate of the transmitter, undersampling occurs. The payload will be lost in undersampling, unlike in the case of oversampling. Figure O.8 shows the scenario in which the missing payload is created and detected using the SN. In this case, the SN is long enough for the receiver to detect the missing payload. The SN of the data packet is increased depending on the sequences of the payload. If one payload is missing, the error can be detected by comparing the SN of the two adjacent DSs. The number of SNs in different states depends on the length of each sub-packet.

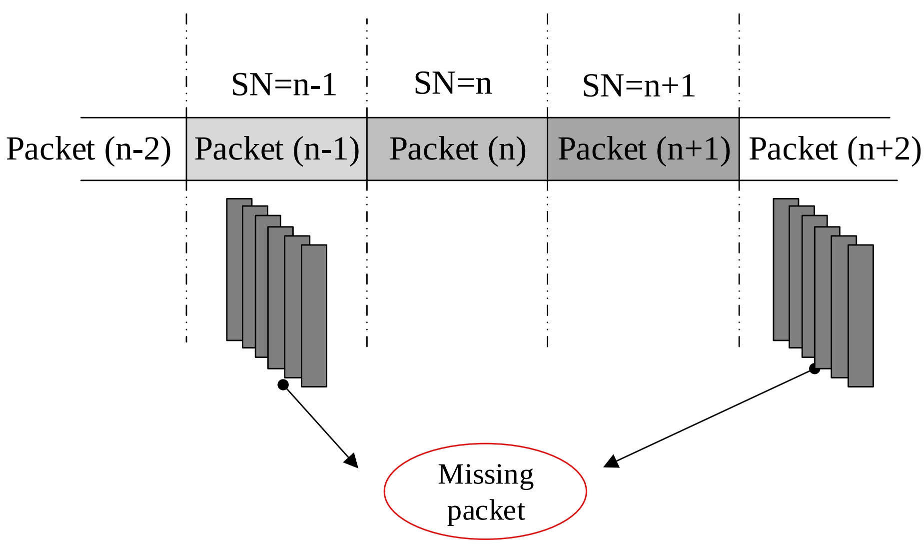


Figure O.8—Error detection in grouping image during the undersampling case

O.2.4 Matched filter decoding and preamble detection

The matched filter is a filter technology achieved by comparing a template signal with the real signal to determine the template signal in the real signal. The matched filter, which is one of the linear filter technologies, optimizes the SNR in the appearance of additive random noise. Matched filters are widely used in almost all wireless communication systems, such as mobile communications and radar systems to maximize the SNR of the system; these filters increase the system performance. To detect preamble positions, the received signal is multiplied by the known preamble signal via the convolution algorithm. After the preamble detection, to decode data, the receiver side also used the matched filter to decode data to improve the system performance. Figure O.9 illustrates the experimental results of C-OOK signals and the preamble position detection based on the matched filter. By creating known patterns as in Figure O.10, the received signal is multiplied with the known preamble signal via the convolution algorithm. From the convolution results, the receiver side can determine which patterns are the most likely the received signal. From there, it is easy to verify the value of signals (0 or 1). Same with the Manchester code, the receiver side can create 16 patterns of 4B6B code to decode data.

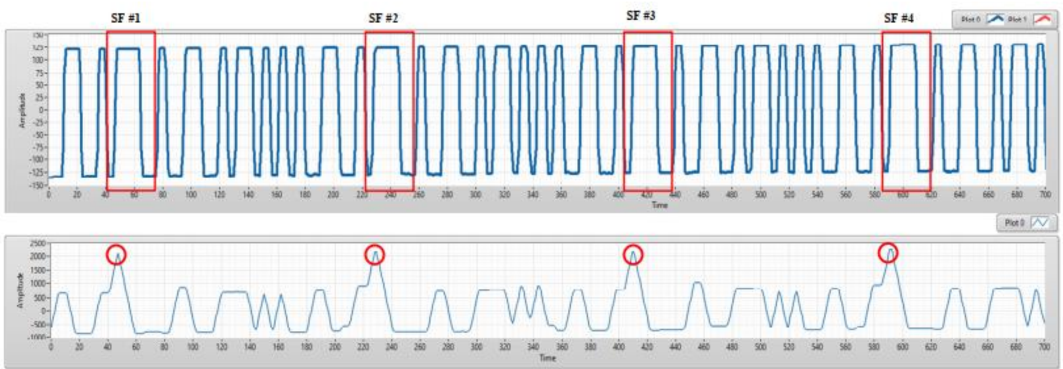


Figure O.9— (a) An experimental result of C-OOK within a rolling image. (b) The results of preamble position detection based on matched filter

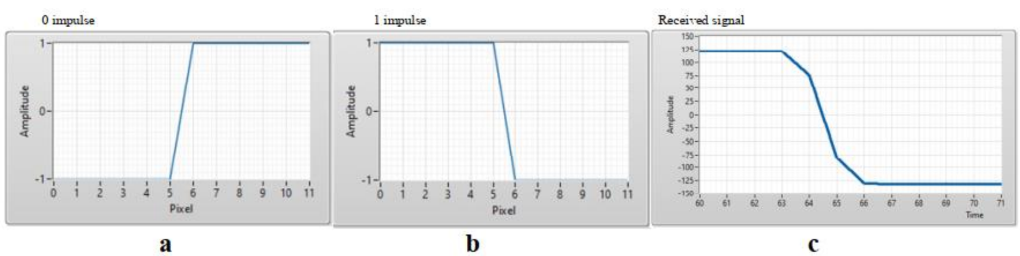


Figure O.10—Manchester code signal patterns and C-OOK received signal. (a) 0 impulse, (b) 1 impulse, (c) C-OOK received signal.

O.3 O-NOMA decoding method

The image sensor in the smartphone camera or other high-speed cameras comprises a number of unit pixels that capture the light intensity coming into it. In the proposed OCC system, as the transmitter is designed to transmit signals through light modulation at the speed of carrier frequency, the camera has the capability of capturing every lighting state by controlling its shutter speed. The camera's rolling shutter mechanism helps to capture LED state as horizontal stripes. Figure O.11 shows the architecture of O-NOMA decoder. The upper half of a bit contains power P_1, and the lower half of a bit contains power level P_2. Figure O.12

illustrates two signal separations and data decoding from a captured LED image using intensity threshold in the image sensor.

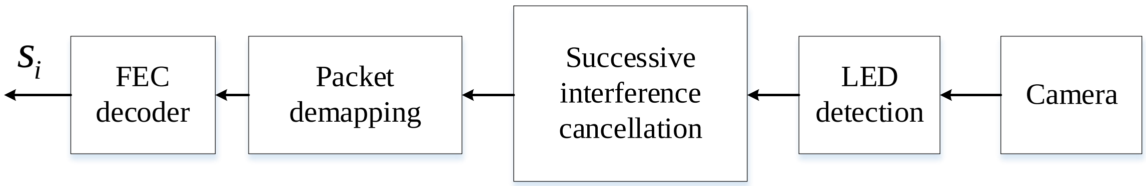


Figure O.11— O-NOMA decoder architecture

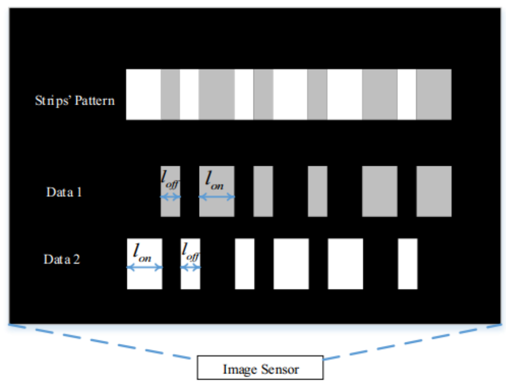


Figure O.12—Two signal separation and data decoding from a captured LED image using intensity threshold in the image sensor

O.4 MIMO-OOK decoding method

Figure O.13 illustrates the MIMO-OOK decoder. The intensity of expected signals and noise signals are illustrated in Figure O.14 and Figure O.15. The MIMO-OOK mode adds a preamble between packets to detect the start packet. This is a special bit sequence, whose definition is based on the RLL code that has been used, and which both the transmitter and receiver know in advance. A preamble has two tasks. Firstly, the receiver can classify the signal light source and unexpected light sources (such as background light and noise light). By using the expected signal, payload data is inputted between two preambles. However, there is no significant change in the intensity of unexpected signals or noise signals.

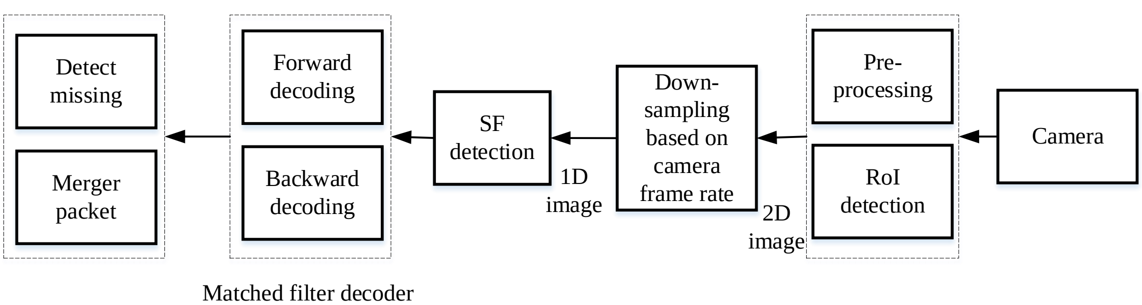


Figure O.13—MIMO-OOK decoder architecture

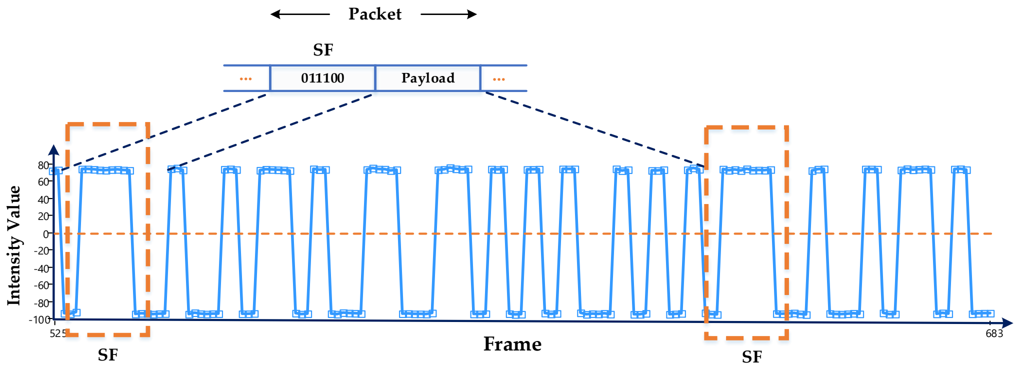


Figure O.14—The intensity of expected signals via RoI signaling

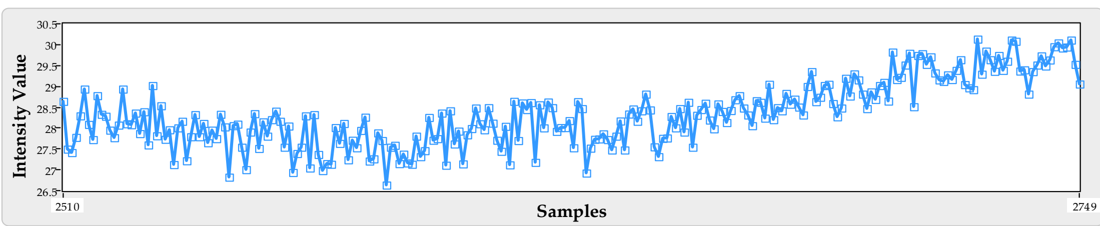


Figure O.15—The intensity of noise signals via RoI signaling

O.5 HOOK-OFDM decoding method

Figure O.16 illustrates the architecture of HOOK-OFDM decoder. For a dual-stream receiver system, the hybrid signal shall be received by a single rolling shutter camera, and it is demodulated as follows:

— The C-OOK decoder will be applied for a low data rate stream.

— The RS-OFDM decoder will be applied for a high data rate stream.

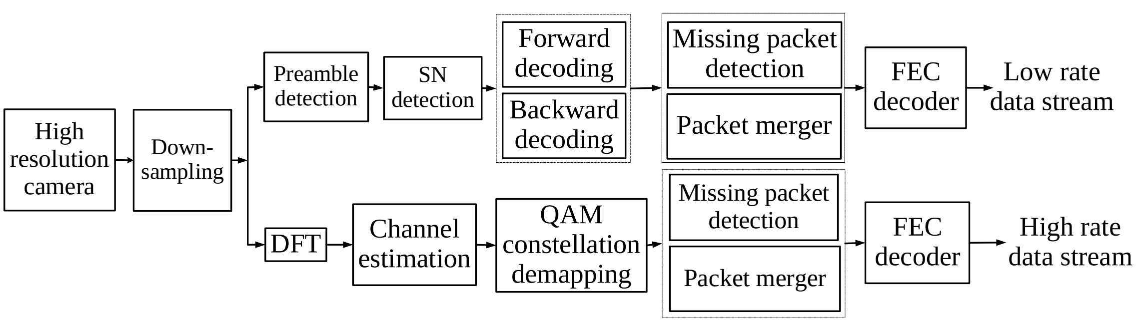


Figure O.16—HOOK-OFDM decoder architecture

O.6 HS2PSK-OFDM decoding method

Figure O.17 illustrates the architecture of HS2PSK-OFDM decoder. The dual-camera receiver system illustrated in Figure O.17 shall be demodulated as follows:

— A low frame rate camera (the frame rate should be greater than the S2-PSK optical clock rate) is to detect the S2-PSK signal. Either a global shutter or a rolling shutter camera shall be used.

— A rolling shutter and high-speed camera are to decode the RS-OFDM signal.

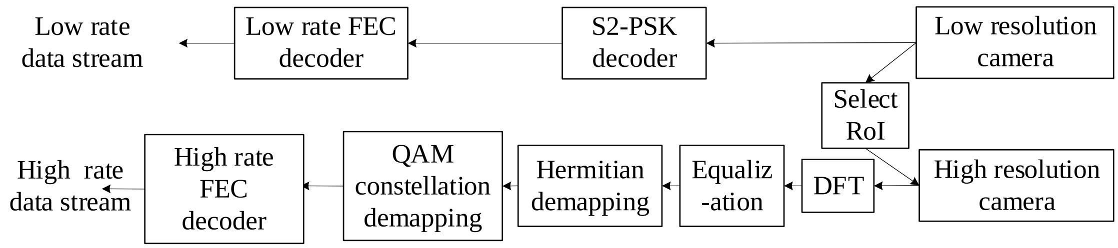


Figure O.17—HS2PSK-OFDM decoder architecture

The following equation illustrates the Hermitian demapping process:

$$Y = [0, Y_1, Y_2, ..., 0, ..., Y_2^*, Y_1^*]$$

$$Y = [0, Y_1, Y_2, ..., Y_{\frac{N}{2}-1}, 0]$$

O.7 BPPM decoding method

The OCC data were decoded from the light intensity received in the IS. The BPPM decoder architecture is illustrated in Figure O.18. In the case of a single LED transmitter, bright and dark stripes were generated according to the ON and OFF states of the LED owing to the camera's rolling shutter effect. In our work, two types of bright stripes were generated, one for the high-power-level signal and the other for the low-power-level signal. The stripe patterns received in the IS are shown in Figure O.19. The thickness of the stripes was dependent on the frequency of the modulated signal. The high-power signals created a brighter stripe than did the low-power signals in the IS. Every two consecutive high-frequency data bits' amplitude was modulated according to the low rate stream. Two different threshold levels (i.e., Th_L and Th_H) were used to retrieve the transmitted data from the stripe pattern. Moreover, Th_L was compared with every bit to detect the high rate data stream, and the Th_H was compared with the intensity level of every two consecutive data bits to detect the low rate stream in this case.

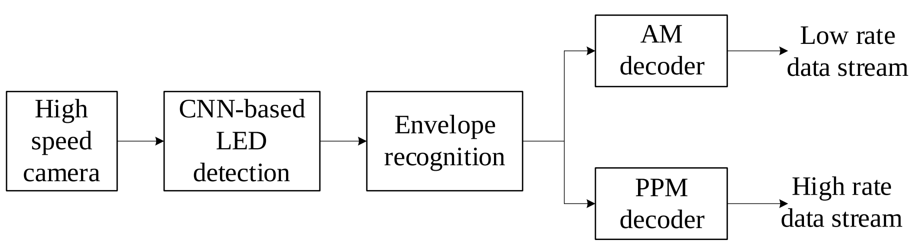


Figure O.18—BPPM decoder architecture

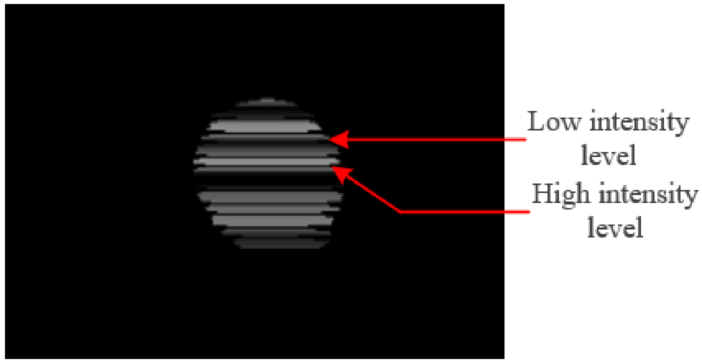


Figure O.19—Received stripe patterns in the camera receiver

Annex P

(informative)

Deep learning for OCC receiver

P.1 Convolution neural network for LED detection with mobility effect

A neural network (NN) is deployed at the receiver to accurately detect the LED in both static and mobile conditions. An LED array is detected as a single LED in the existing literature. However, each LED in an LED array can be detected using the proposed NN technique. The NN can classify large image datasets with remarkable characteristics in several spatial layers and automatically learn from data through backpropagation. Figure P.1 illustrates the training architecture of neural network-based stripe pattern reformation.

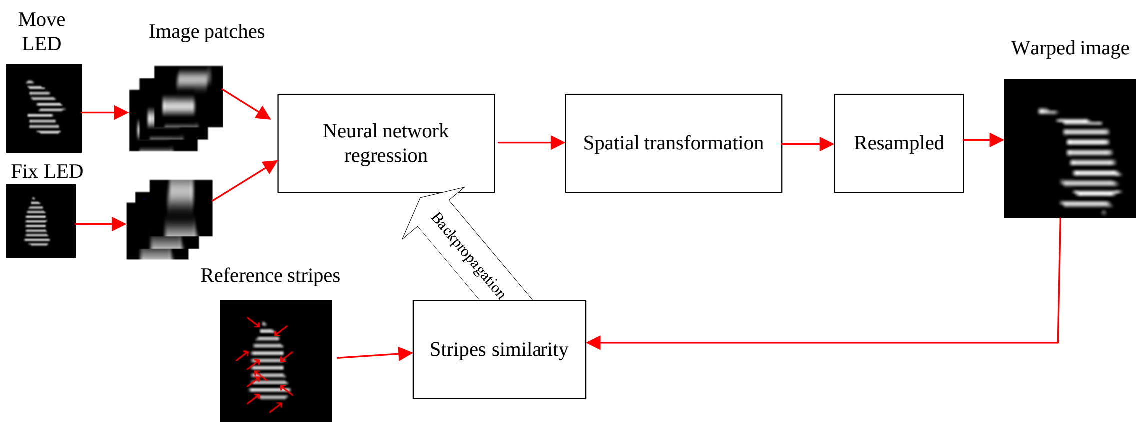


Figure P.1—Training architecture of neural network-based stripe pattern reformation

Background lights and neighboring LEDs can create noise and interference in the image sensor, respectively. On the other hand, interference occurs if a LED light source unexpectedly appears inside the image sensor FOV. In particular, after detection, several frames are captured and analyzed. If the stripe pattern of a specific area is changed in the subsequent frames, it is recognized as the source LED. Otherwise, it is categorized as the interfering LED and subsequently filters out from the image frame.

P.2 Support vector machine (SVM) classifier

In Figure P.2, the block diagram delineates the overall architecture of the accurate data-transmitting LED detection scheme. On the transmitter side, numerous LED regions were present. The LED optical signal was modulated by modulation at a frequency level between 2–4 kHz before sending to the receiver to attenuate the flickering issue in a significant margin. Concerning the transmitting LEDs and other sources of interference, they are not modulated in that particular frequency. The image sensor captured the projection of all these light-emitting sources. Interference sources were dispelled when a trained CNN model was used. All the possible LED sources were detected and segmented using image processing techniques. Due to the rolling shutter effect of the CMOS-based image sensor, each image frame gets striated of white and black shades. Afterward, necessary geometrical features have been extracted to classify and recognize accurate data-transmitting regions from the range of all possible regions.

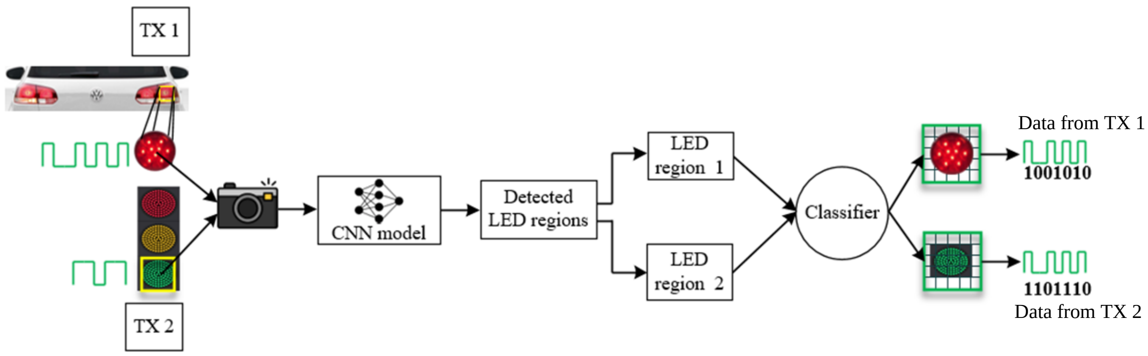


Figure P.2—The architecture of the accurate data transmitting LED detection scheme