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The Consultative Committee for Space Data Systems

Recommendation for Space Data System Standards

OPTICAL COMMUNICATIONS PHYSICAL LAYER

RECOMMENDED STANDARD

CCSDS 141.0-B-1

BLUE BOOK
August 2019

CCSDS

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FOREWORD

This document is a CCSDS Recommended Standard for the Physical Layer of signals to be used in optical communications systems of space missions. It was contributed to CCSDS by NASA. The Physical Layer concepts described herein are intended for missions that are cross supported between Agencies of the CCSDS.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CCSDS has processes for identifying patent issues and for securing from the patent holder agreement that all licensing policies are reasonable and non-discriminatory. However, CCSDS does not have a patent law staff, and CCSDS shall not be held responsible for identifying any or all such patent rights.

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- United States Geological Survey (USGS)/USA.

DOCUMENT CONTROL

Document	Title	Date	Status
CCSDS 141.0-B-1	Optical Communications Physical Layer, Recommended Standard, Issue 1	August 2019	Original issue

CONTENTS

CONTENTS (continued)

1 INTRODUCTION

1.1 PURPOSE

The purpose of this Recommended Standard is to specify the Physical Layer characteristics of free-space optical communications systems used by space missions. The primary application addressed in this issue of the Recommended Standard is space-to-ground and ground-to-space photon starved links through an atmospheric channel; use of the Recommended Standard for other applications or operating conditions is not precluded. When provided with a sequence of pulsed and non-pulsed slots produced by the Coding and Synchronization sublayer (see reference [1]), this specification describes the required Physical Layer characteristics of the telemetry, beacon, and optional data transmission accompanying a beacon.

1.2 SCOPE

This Recommended Standard defines Physical Layer schemes in terms of the signal characteristics and procedures involved in the physical transmission of the optical signals. It does not specify

    a) individual implementations or products;

    b) the methods or technologies required to perform the procedures; or

    c) the management activities required to configure and control the system.

Issue 1 of this Recommended Standard provides a specification for High Photon Efficiency (HPE) optical communications, in which the photon-efficiency of the link is of primary concern.[1] Details of the design and implementation of HPE systems can be found in references [D5], [D6], and [D7].

1.3 APPLICABILITY

This Recommended Standard applies to the creation of Agency standards and to the future data communications over optical space links between CCSDS Agencies in cross-support situations. It includes comprehensive specifications of the data formats and procedures for inter-Agency cross support. It is neither a specification of, nor a design for, real systems that may be implemented for existing or future missions.

The Recommended Standard specified in this document is to be invoked through the normal standards program of each CCSDS Agency and is applicable to those missions for which cross support based on capabilities described in this Recommended Standard is anticipated. Where mandatory capabilities are clearly indicated in sections of this Recommended Standard, they must be implemented when this document is used as a basis for cross support.

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[1] A subsequent issue of this Recommended Standard may provide a specification for optical on-off-keying and/or high-data-rate optical communications.

Where options are allowed or implied, implementation of these options is subject to specific bilateral cross support agreements between the Agencies involved.

1.4   RATIONALE

The rationale for producing this Recommended Standard is that it facilitates cross support at the physical layer of optical communications systems used by CCSDS member agencies. Such cross support requires specification of a set of allowable center frequencies of transmission, along with other physical layer characteristics of the signal.

The CCSDS believes it is important to document the rationale underlying the recommendations chosen so that future evaluations of proposed changes or improvements will not lose sight of previous decisions. The rationale for the specifications making up this Recommended Standard is expected to be documented in a forthcoming CCSDS Informational Report.

1.5   DOCUMENT STRUCTURE

This document is divided into five numbered sections and four annexes:

a) section 1 presents the purpose, scope, applicability, rationale, document structure, definitions, and references;

b) section 2 provides an overview of the architecture and summary of functions of the Physical Layer;

c) section 3 specifies HPE telemetry signal characteristics;

d) section 4 specifies HPE beacon and optional accompanying data transmission signal characteristics;

e) section 5 lists the managed parameters;

f) annex A is a Protocol Implementation Conformance Statement (PICS) Proforma;

g) annex B discusses security issues;

h) annex C lists acronyms used within this document;

i) annex D provides a list of informative references.

1.6   NOMENCLATURE

1.6.1   NORMATIVE TEXT

The following conventions apply throughout this Specification:

a) the words 'shall' and 'must' imply a binding and verifiable specification;

b) the word 'should' implies an optional, but desirable, specification;

c) the word 'may' implies an optional specification;

d) the words 'is', 'are', and 'will' imply statements of fact.

1.6.2 INFORMATIVE TEXT

In the normative sections of this document, informative text is set off from the normative specifications either in notes or under one of the following subsection headings:

– Overview;

– Background;

– Rationale;

– Discussion.

1.7 CONVENTIONS

In this document, the following convention is used to identify each bit in an N-bit field. The first bit in the field to be transmitted (i.e., the most left justified when drawing a figure) is defined to be 'Bit 0', the following bit is defined to be 'Bit 1', and so on up to 'Bit N-1'. When the field is used to express a binary value (such as a counter), the Most Significant Bit (MSB) shall be the first transmitted bit of the field, that is, 'Bit 0' (see figure 1-1).

BIT 0   BIT N-1

N-BIT DATA FIELD

FIRST BIT TRANSMITTED = MSB
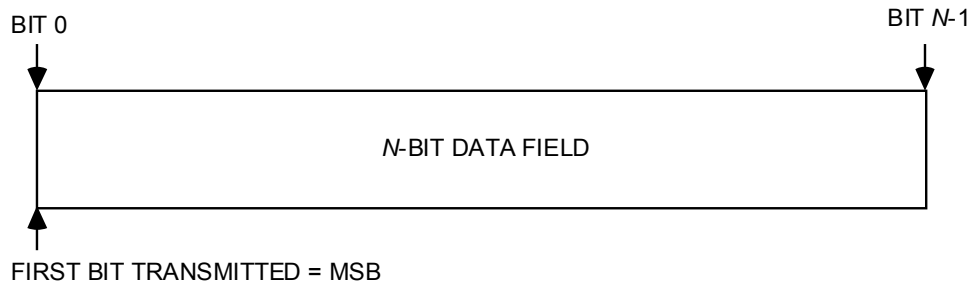
Figure 1-1: Bit Numbering Convention

In accordance with standard data-communications practice, data fields are often grouped into 8-bit 'words' which conform to the above convention. Throughout this specification, such an 8-bit word is called an 'octet'. The numbering for octets within a data structure starts with '0'.

NOTE – Throughout this document, 'bit' refers to the contents of the transfer frames. A bit is a binary digit transferred between the Data Link Protocol sublayer and the Coding and Synchronization sublayer. Other symbols, whether binary or nonbinary, will be referred to by other names, such as 'binary digits'. It should be understood that the ordering conventions described above apply equally to other types of symbols.

1.8   REFERENCES

The following publications contain provisions which, through reference in this text, constitute provisions of this document. At the time of publication, the editions indicated were valid. All publications are subject to revision, and users of this document are encouraged to investigate the possibility of applying the most recent editions of the publications indicated below. The CCSDS Secretariat maintains a register of currently valid CCSDS publications.

[1]   *Optical Communications Coding and Synchronization*. Issue 1. Recommendation for Space Data System Standards (Blue Book), CCSDS 142.0-B-1. Washington, D.C.: CCSDS, August 2019.

[2]   *IEEE Standard for Definitions of Terms for Antennas*. Revision of IEEE Std 145-1993. IEEE Std 145-2013. New York: IEEE, 2014.

2   OVERVIEW

2.1   ARCHITECTURE

Figure 2-1 illustrates the relationship of this Recommended Standard to the Open Systems Interconnection (OSI) reference model (reference [D1]). Two sublayers of the Data Link Layer are defined for CCSDS space link protocols. The Data Link Protocol sublayer provides functions for producing Transfer Frames; possible Space Data Link Protocols using optical communications are the TM Space Data Link Protocol (reference [D2]), the AOS Space Data Link Protocol (reference [D3]), and the Unified Space Data Link Protocol (USLP) (reference [D8]). The Optical Coding and Synchronization protocol (reference [1]) provides the functions of the Coding and Synchronization sublayer of the Data Link Layer for transferring Transfer Frames over an optical space link. The Optical Communications Physical Layer specified in this Recommended Standard provides the required characteristics of the Physical Layer transmission from space to ground and from ground to space.
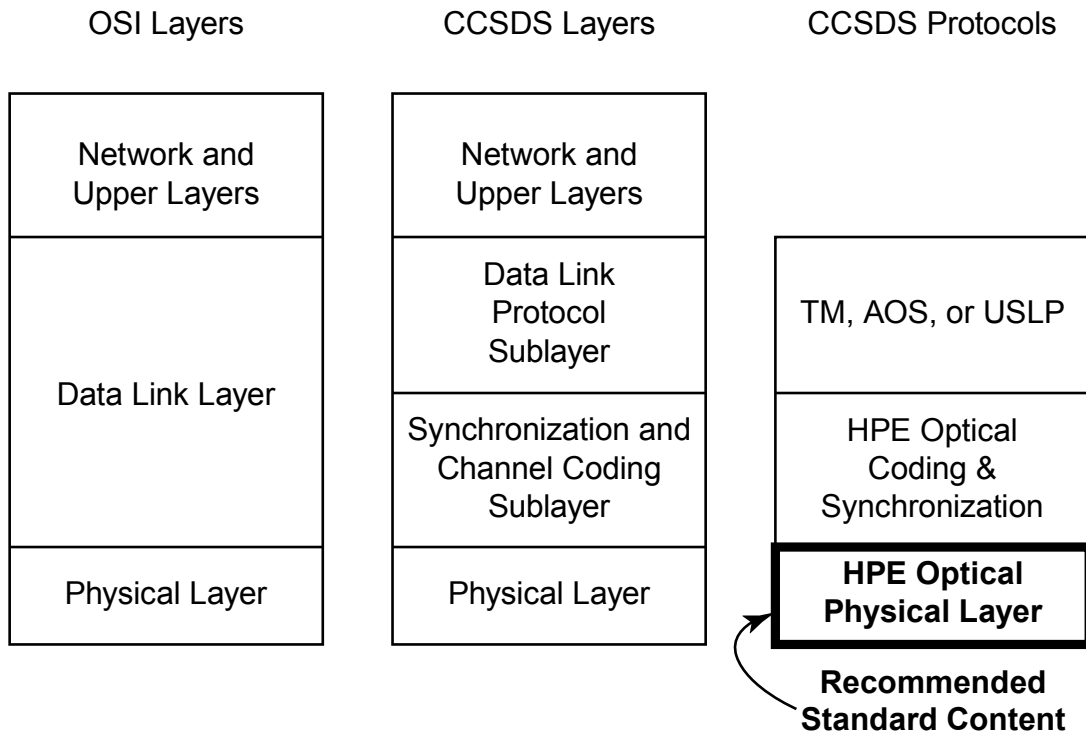
Figure 2-1: Relationship with OSI Layers

2.2   SUMMARY OF FUNCTIONS

The Optical Communications Physical Layer specifies the physical characteristics of the telemetry signal and, separately, the physical characteristics of the beacon and optional telecommand signal. In a typical application, a spacecraft transmits telemetry to a ground station, and a ground station transmits a beacon and optional transfer frames to the spacecraft.

For each of the telemetry and beacon and optional data transmission specifications, this Recommended Standard defines the transmission laser's required center frequency, tuning range, linewidth, in-band and spillover emissions, polarization, modulation, pulse shape, timing jitter, and supported slot widths.

The overall architecture of the optical communications system is shown in figure 2-2. Throughout the communications session, the optical Terminal A transmits a beacon, together with optional AOS or USLP transfer frames. The Terminal B receiver locks onto the beacon and uses it to assist in accurately pointing its optical transmitter. Any AOS/USLP transfer frames are also decoded onboard. Telemetry is transmitted from terminal B and received by Terminal A. This Recommended Standard specifies the physical characteristics of the Terminal A and Terminal B transmitters. In a typical application, Terminal A on the ground transmits an uplink beacon and optional AOS/USLP transfer frames to Terminal B in space, and Terminal B transmits a downlink telemetry signal to Terminal A.
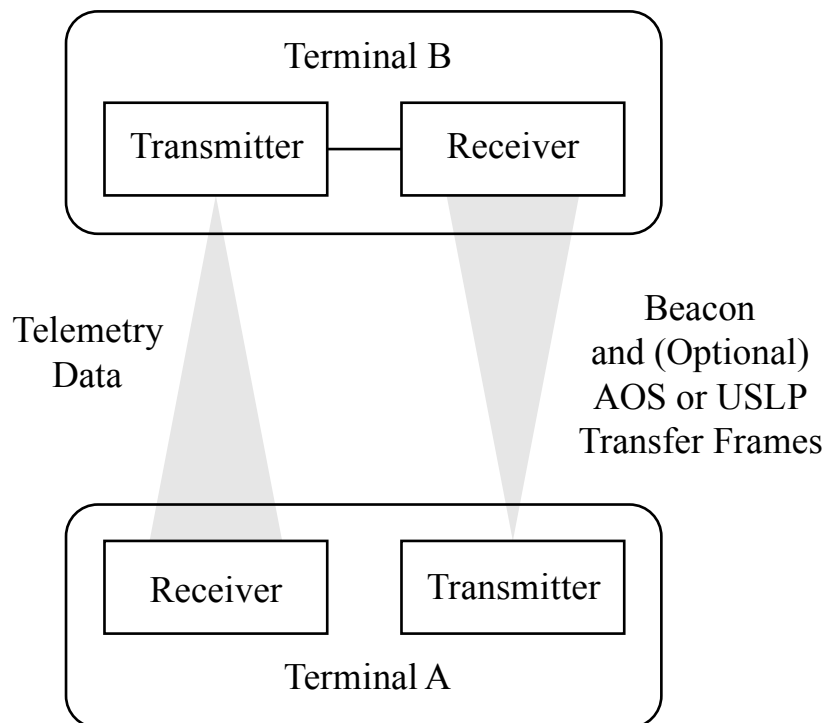

Figure 2-2: Overall Architecture of the Optical Communications System

3 HPE TELEMETRY SIGNAL CHARACTERISTICS

3.1 OVERVIEW

At the sending end, a binary vector is received from the Coding and Synchronization sublayer, as defined in reference [1], indicating a sequence of slots in which light pulses are to be present (1) or absent (0). The physical characteristics of these pulses at the sending end are described below. At the receiving end, the Physical Layer delivers slot measurements to the Coding and Synchronization sublayer.

3.2 CENTER FREQUENCY

The center frequency shall be $193.1 + n \times 0.1$ THz, where n is an integer ranging from -18 to 28.

NOTE – These center frequencies in the optical C-band are a subset of those defined in the ITU-T G.694.1 frequency grid with 100 GHz channel spacing (reference [D4]). The frequencies range from 191.3 THz to 195.9 THz and correspond to wavelengths in a vacuum ranging from 1530.33 nm to 1567.13 nm.

3.3 CENTER FREQUENCY TOLERANCE

The transmitter center frequency shall be accurate to within a tolerance of $\pm$ 10 GHz.

3.4 LASER LINEWIDTH

The modulated laser linewidth shall be less than 6.25 GHz, measured at full width, $1/e^2$ of maximum, over a time scale of 100 ms.

3.5 IN-BAND AND SPILLOVER EMISSIONS

The laser shall transmit 95 percent of its energy within $\pm$ 10 GHz of its center frequency.

3.6 POLARIZATION

3.6.1 POLARIZATION TYPE

Polarized laser emission is optional. When polarized, the laser emission exiting the terminal aperture shall be Right-Hand Circularly Polarized (RHCP) as defined in reference [2].

3.6.2 POLARIZATION EXTINCTION RATIO

When polarized emission is used, the polarization extinction ratio shall be greater than 10 dB.

3.7 MODULATION

The binary vector received from the Coding and Synchronization sublayer defined in reference [1] shall be used to modulate the intensity of emitted light within each slot, using On-Off Keying (OOK).

NOTE – A modulation of Pulse Position Modulation (PPM) at the Coding and Synchronization sublayer gives rise to OOK at the Physical Layer, in the sense that a light pulse is present or absent in each slot.

3.8 TIMING JITTER

The Root Mean Square (RMS) pulse timing jitter shall be less than 10 percent of the slot width.

3.9 SLOT WIDTH

The slot width T shall be 0.125, 0.25, 0.5, 1, 2, 4, 8, 16, 32, 64, 128, 256, or 512 ns.

3.10 PULSE REPETITION RATES

The laser shall support a range of Pulse Repetition Rates (PRRs) corresponding to the slot width(s) and PPM order(s) used by the communications link.

NOTE – For example, in a system using 1 ns slots with 16-PPM and 4 slots of guard time, pulses could be as close as 5 ns and as far apart as 35 ns, center to center, corresponding to a PRR range of 28.57 to 200 MHz.

4 HPE BEACON AND OPTIONAL ACCOMPANYING DATA TRANSMISSION SIGNAL CHARACTERISTICS

4.1 OVERVIEW

At the sending end, a binary vector is received from the Coding and Synchronization sublayer, as defined in reference [1], indicating a sequence of slots in which light pulses are to be present (1) or absent (0). The physical characteristics of these pulses at the sending end are described below. At the receiving end, the Physical Layer delivers slot measurements to the Coding and Synchronization sublayer.

4.2 CENTER FREQUENCY

The center frequency shall be tunable to any frequency within ±26 GHz of 280.18 THz, 281.72 THz, or 291.06 THz.

NOTE – These center frequencies correspond to wavelengths in vacuum of 1070 nm, 1064.15 nm, and 1030 nm, respectively.

4.3 CENTER FREQUENCY TOLERANCE

The transmitter center frequency shall be accurate to within a tolerance of ±26.5 GHz.

4.4 LASER LINEWIDTH

The laser linewidth shall not exceed 53 GHz, measured at full width, $1/e^2$ of maximum, over a time scale of 100 ms.

4.5 IN-BAND AND SPILLOVER EMISSIONS

The laser shall transmit 95 percent of its energy within ±50 GHz of its center frequency.

4.6 MODULATION

4.6.1 OVERVIEW

Data transmission is optional.

4.6.2 WHEN DATA TRANSMISSION IS NOT USED

When data transmission is not used, the beacon transmission shall be a 3.8145 kHz square wave. The period of the square wave is 262,144 ns, that is, an alternating sequence of pulsed and non-pulsed slots of duration 131,072 ns.

4.6.3   WHEN DATA TRANSMISSION IS USED

4.6.3.1   General

When data transmission is used, the binary vector received from the Coding and Synchronization sublayer defined in reference [1] shall be used to modulate the intensity of emitted light within each slot, using OOK.

NOTES

1   A modulation of PPM at the Coding and Synchronization sublayer gives rise to OOK at the Physical Layer, in the sense that a light pulse is present or absent in each slot.

2   The transmission is not required to be polarized

4.6.3.2   Slot Widths

The slot width shall be 65,536 ns.

NOTE –   This Recommended Standard can be compatible with systems using substantially narrower pulse shapes that convey additional, higher-rate telecommand data than is specified in this Recommended Standard. Such 'nested outer modulations' are not specified by this Recommended Standard, nor are they necessarily precluded by this Recommended Standard.

4.7   TIMING JITTER

The RMS pulse timing jitter shall be less than 10 percent of the slot width.

5   MANAGED PARAMETERS

The managed parameters for HPE signaling shall be those specified in table 5-1.

Table 5-1: Managed Parameters for HPE

Managed Parameter	Allowed Values
n, the telemetry signaling center frequency selection parameter	−18 to 28
Telemetry signaling slot width	0.125, 0.25, 0.5, 1, 2, 4, 8, 16, 32, 64, 128, 256, or 512 ns
Telemetry signaling polarized transmission	Used or Not Used
Beacon frequency	280.18, 281.72, or 291.06 THz
Data transmission	Used or Not Used

ANNEX A

PROTOCOL IMPLEMENTATION
CONFORMANCE STATEMENT PROFORMA

(NORMATIVE)

A1   INTRODUCTION

A1.1   OVERVIEW

This annex provides the Protocol Implementation Conformance Statement (PICS) Requirements List (RL) for an implementation of Optical Communications Physical Layer, (CCSDS 141.0-B-1). The ICS for an implementation is generated by completing the RL in accordance with the instructions below. An implementation claiming conformance must satisfy the mandatory requirements referenced in the RL.

The RL support column in this annex is blank. An implementation's completed RL is called the ICS. The ICS states which capabilities and options have been implemented. The following can use the ICS:

− the implementer, as a checklist to reduce the risk of failure to conform to the standard through oversight;

− a supplier or potential acquirer of the implementation, as a detailed indication of the capabilities of the implementation, stated relative to the common basis for understanding provided by the standard ICS proforma;

− a user or potential user of the implementation, as a basis for initially checking the possibility of interworking with another implementation (it should be noted that, while interworking can never be guaranteed, failure to interwork can often be predicted from incompatible PICSes);

− a tester, as the basis for selecting appropriate tests against which to assess the claim for conformance of the implementation.

A1.2   ABBREVIATIONS AND CONVENTIONS

The RL consists of information in tabular form. The status of features is indicated using the abbreviations and conventions described below.

Item Column

The item column contains sequential numbers for items in the table.

Description Column

The description column contains a brief description of the item. It implicitly means 'Is this item supported by the implementation?'

Reference Column

The reference column indicates the relevant subsection of *Optical Communications Coding and Synchronization*, CCSDS 142.0-B-1 (this document).

Status Column

The status column uses the following notations:

M   mandatory.

O   optional.

O.*i*   qualified optional – for a group of related optional items labeled by the same

              numeral *i*, it is mandatory to support at least one of the items.

C:<status>   indicates that the status applies for the given subordinate item when

              the parent item is supported, and is not applicable otherwise.

1+   One or more of the allowed values must be supported.

N/A   not applicable.

Support Column Symbols

The support column is to be used by the implementer to state whether a feature is supported by entering Y, N, or N/A, indicating:

Y   Yes, supported by the implementation.

N   No, not supported by the implementation.

N/A   Not applicable.

The support column should also be used, when appropriate, to enter values supported for a given capability.

A1.3   INSTRUCTIONS FOR COMPLETING THE RL

An implementer shows the extent of compliance to the Recommended Standard by completing the RL; that is, the state of compliance with all mandatory requirements and the options supported are shown. The resulting completed RL is called an ICS. The implementer shall complete the RL by entering appropriate responses in the support or values supported

column, using the notation described in A1.2. If a conditional requirement is inapplicable, N/A should be used. If a mandatory requirement is not satisfied, exception information must be supplied by entering a reference Xi, where i is a unique identifier, to an accompanying rationale for the noncompliance.

A2   ICS PROFORMA FOR OPTICAL COMMUNICATIONS CODING AND SYNCHRONIZATION (CCSDS 142.0-B-1)

A2.1   GENERAL INFORMATION

A2.1.1   Identification of ICS

Date of Statement (DD/MM/YYYY)	
ICS serial number	
System Conformance statement cross-reference	

A2.1.2   Identification of Implementation Under Test (IUT)

Implementation Name	
Implementation Version	
Special Configuration	
Other Information	

A2.1.3   Identification of Supplier

Supplier	
Contact Point for Queries	
Implementation Name(s) and Versions	
Other information necessary for full identification, e.g., name(s) and version(s) for machines and/or operating systems; System Name(s)	

A2.1.4   Identification of Specification

CCSDS 142.0-B-1	
Have any exceptions been required? NOTE – A YES answer means that the implementation does not conform to the Recommended Standard. Non-supported mandatory capabilities are to be identified in the ICS, with an explanation of why the implementation is nonconforming.	Yes [ ] No [ ]

A2.1.5   Requirements list

HPE Telemetry signaling:

Item	Description	Reference	Status	Values Allowed	Item Supported or Values Supported
HPE-1	Center frequency index	3.2	1+	-18 to 28	
HPE-2	Center frequency tolerance	3.3	M	± 10 GHz	
HPE-3	Laser linewidth	3.4	M	< 6.25 GHz	
HPE-4	In-band and spillover emissions	3.5	M	95% within ± 10 GHz	
HPE-5	Polarized emission	3.6	O	N/A	
HPE-5.1	Polarization type	3.6.1	C:M	RHCP	
HPE-5.2	Polarization extinction ratio	3.6.2	C:M	>10 dB	
HPE-6	Modulation	3.7	M	OOK	
HPE-7	Timing jitter	3.8	M	<10% of slot	
HPE-8	Slot width	3.9	M	0.125, 0.25, 0.5, 1, 2, 4, 8, 16, 32, 64, 128, 256, or 512 ns	
HPE-9	PRRs	3.10	M	N/A	

HPE beacon and optional accompanying data transmission signaling:

Item	Description	Reference	Status	Values Allowed	Item Supported or Values Supported
HPE-10	Center frequency	4.2	1+	within ±26 GHz of 280.18, 281.72, 291.06 THz	
HPE-11	Center frequency tolerance	4.3	M	±26.5 GHz	
HPE-12	Laser linewidth	4.4	M	53 GHz	
HPE-13	In-band and spillover emissions	4.5	M	95% within ± 50 GHz	
HPE-14	Telecommand data transmission not used	4.6.2	O.1	N/A	
HPE-14.1	Beacon	4.6.2	C:M	3.8145 KHz square wave	
HPE-15	Telecommand data transmission used	4.6.3	O.1	N/A	
HPE-15.1	Slot width	4.6.3.2	C:M	65,536 ns	
HPE-16	Timing jitter	4.7	M	<10% of slot	

ANNEX B

SECURITY, SANA, AND PATENT CONSIDERATIONS

(INFORMATIVE)

B1   SECURITY CONSIDERATIONS

B1.1   SECURITY BACKGROUND

It is assumed that security is provided by encryption, authentication methods, and access control to be performed at a layer above the physical layer and coding and synchronization sublayer. Mission and service providers are expected to select from recommended security methods, suitable to the specific application profile. Specification of these security methods and other security provisions is outside the scope of this Recommended Standard. The Physical Layer has the objective of delivering data with the minimum possible amount of residual errors. The associated channel coding as described in reference [1] must be used to ensure that residual errors are detected and the frame flagged. There is an extremely low probability of additional undetected errors that may escape this scrutiny. These errors may affect the encryption process in unpredictable ways, possibly affecting the decryption stage and producing data loss, but will not compromise the security of the data.

B1.2   SECURITY CONCERNS

Security concerns in the areas of data privacy, authentication, access control, availability of resources, and auditing are to be addressed in higher layers and are outside the scope of this Recommended Standard.

B1.3   CONSEQUENCES OF NOT APPLYING SECURITY

There are no specific security measures prescribed for the Physical Layer. Therefore consequences of not applying security are only imputable to the lack of proper security measures in other layers. Residual undetected errors may produce additional data loss when the link carries encrypted data.

B2   SANA CONSIDERATIONS

The recommendations of this document do not require any action from SANA.

B3   PATENT CONSIDERATIONS

No patents are known to relate to this Recommended Standard.

ANNEX C

ABBREVIATIONS AND TERMS

(INFORMATIVE)

C1   INTRODUCTION

This annex lists key abbreviations and terms that are used throughout this Recommended Standard.

C2   ABBREVIATIONS

AOS	Advanced Orbiting Systems
HPE	high photon efficiency
ITU	International Telecommunication Union
MSB	most significant bit
OOK	on-off keying
OSI	Open Systems Interconnection
PPM	pulse position modulation
PRR	pulse repetition rate
RHCP	right-hand circular polarization
RMS	root mean square
RZ50	50-percent return-to-zero
TM	telemetry
USLP	Unified Space Data Link Protocol

C3   TERMS

center frequency: The central frequency of a laser beam occupying a range of frequencies.

laser linewidth: The spectral linewidth of a laser beam.

optical pulse: An emission of photons, often constrained with respect to its amplitude, shape, and duration.

polarization extinction ratio: The ratio of optical powers of perpendicular polarization.

pulse repetition rate, PRR: The number of emitted pulses per second, or the inverse temporal pulse spacing.

right-hand circular polarization, RHCP: A circularly polarized wave in which the electric field vector rotates in a right-hand sense, with respect to the direction of propagation.

spillover emissions: The energy of an emission that is outside of a defined spectral band.

ANNEX D

INFORMATIVE REFERENCES

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