The Consultative Committee for Space Data Systems

Draft Recommendation for
Space Data System Standards

OPTICAL COMMUNICATIONS PHYSICAL LAYER

DRAFT RECOMMENDED STANDARD

CCSDS 141.0-R-1

RED BOOK
November 2017

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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.

Through the process of normal evolution, it is expected that expansion, deletion, or modification of this document may occur. This Recommended Standard is therefore subject to CCSDS document management and change control procedures, which are defined in the *Organization and Processes for the Consultative Committee for Space Data Systems* (CCSDS A02.1-Y-4). Current versions of CCSDS documents are maintained at the CCSDS Web site:

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PREFACE

This document is a draft CCSDS Recommended Standard. Its 'Red Book' status indicates that the CCSDS believes the document to be technically mature and has released it for formal review by appropriate technical organizations. As such, its technical contents are not stable, and several iterations of it may occur in response to comments received during the review process.

Implementers are cautioned **not** to fabricate any final equipment in accordance with this document's technical content.

Recipients of this draft are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation.

DOCUMENT CONTROL

Document	Title	Date	Status
CCSDS 141.0-R-1	Optical Communications Physical Layer, Draft Recommended Standard, Issue 1	November 2017	Current draft
EC1	Editorial update	November 2017	Corrects a reference problem

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 references [D4] and [D5]), this specification describes the required Physical Layer characteristics of the downlink and uplink transmissions.

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]

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.

[1] A subsequent issue of this Recommended Standard may provide a specification for low-complexity 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 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 downlink signal characteristics;

d) section 4 specifies HPE uplink 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, i.e., ‘Bit 0’ (see figure 1-1).

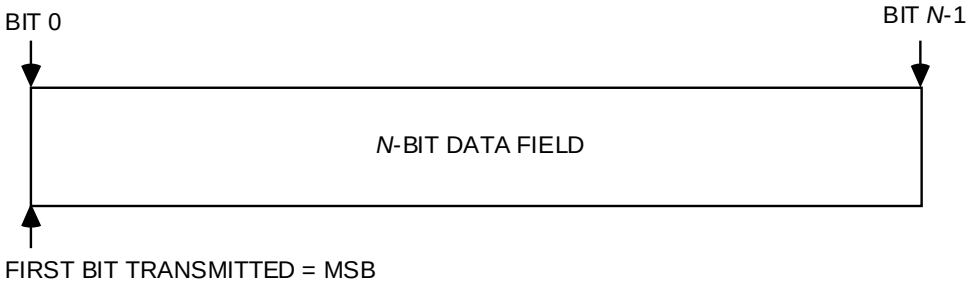

Figure 1-1: Bit Numbering Convention

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*. Proposed Draft Recommendation for Space Data System Standards (Proposed Red Book), CCSDS 142.0-R. Forthcoming.

[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 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; examples are the TM Space Data Link Protocol, (reference [D2]), and the AOS Space Data Link Protocol (reference [D3]). 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.

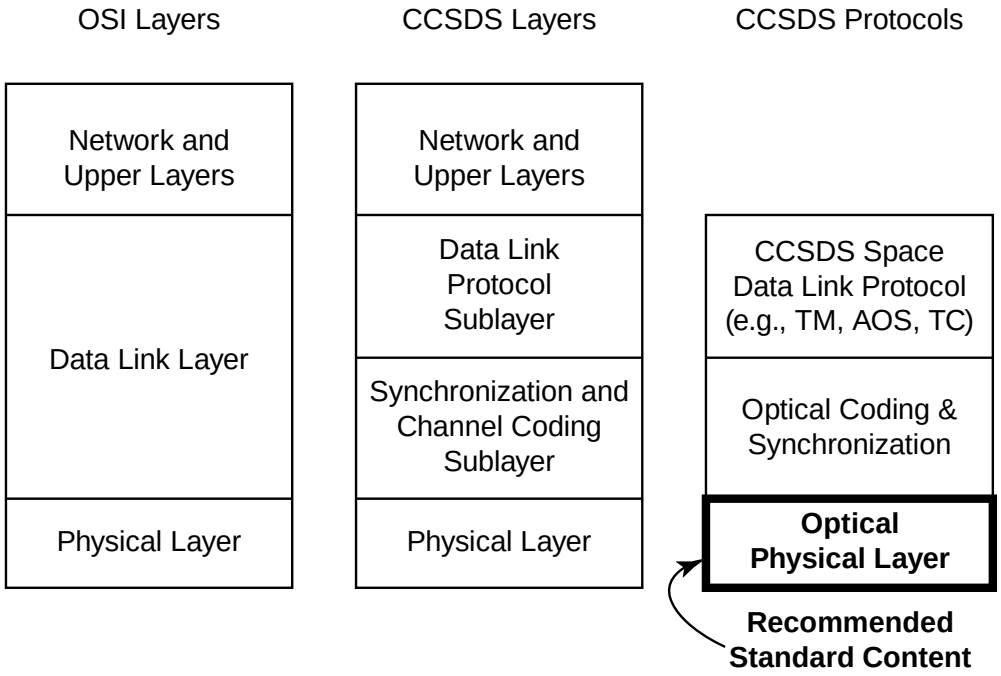

Figure 2-1: Relationship with OSI Layers

2.2 SUMMARY OF FUNCTIONS

The Optical Communications Physical Layer specifies the physical characteristics of the downlink and, separately, the physical characteristics of the uplink.

For each of the downlink and uplink 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.

3 HPE DOWNLINK SIGNAL CHARACTERISTICS

3.1 CENTER FREQUENCY

The center frequency shall be 191.6 + n×0.1 THz, where n is an integer ranging from 0 to 43.

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 [D6]). The frequencies range from from 191.6 THz to 195.9 THz and correspond to wavelengths in vacuum ranging from 1530.33 nm to 1564.68 nm.

3.2 CENTER FREQUENCY TOLERANCE

The transmitter center frequency shall be accurate to within a tolerance of ± 10 GHz.

3.3 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.

3.4 IN-BAND AND SPILLOVER EMISSIONS

The laser shall transmit 95 percent of its energy within ± 10 GHz of its center frequency.

3.5 POLARIZATION

3.5.1 POLARIZATION TYPE

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

3.5.2 POLARIZATION EXTINCTION RATIO

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

3.5.3 MODULATION

The binary vector received from the Coding and Synchronization sublayer 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.

3.5.4 PULSE SHAPE/EYE DIAGRAM

The reference pulse intensity shape of the modulated communications beam transmitted by a terminal shall be a single period of a 50-percent return-to-zero (RZ50) waveform defined by

$$I_{REF}(t) = \begin{cases} \cos^2\left(\pi \dfrac{V(t)}{V_\pi} + \dfrac{\pi}{4}\right) & 0 \le t \le T \\ 0 & otherwise \end{cases}$$

where $V(t) = \dfrac{V_\pi}{4}\cos(2\pi f t)$;

V_π is the voltage required to induce a π phase shift in the modulator; and

$f = 1/T$ is the slot rate.

NOTE – The reference pulse shape for a slot rate of 1 GHz is shown in figure 3-1.

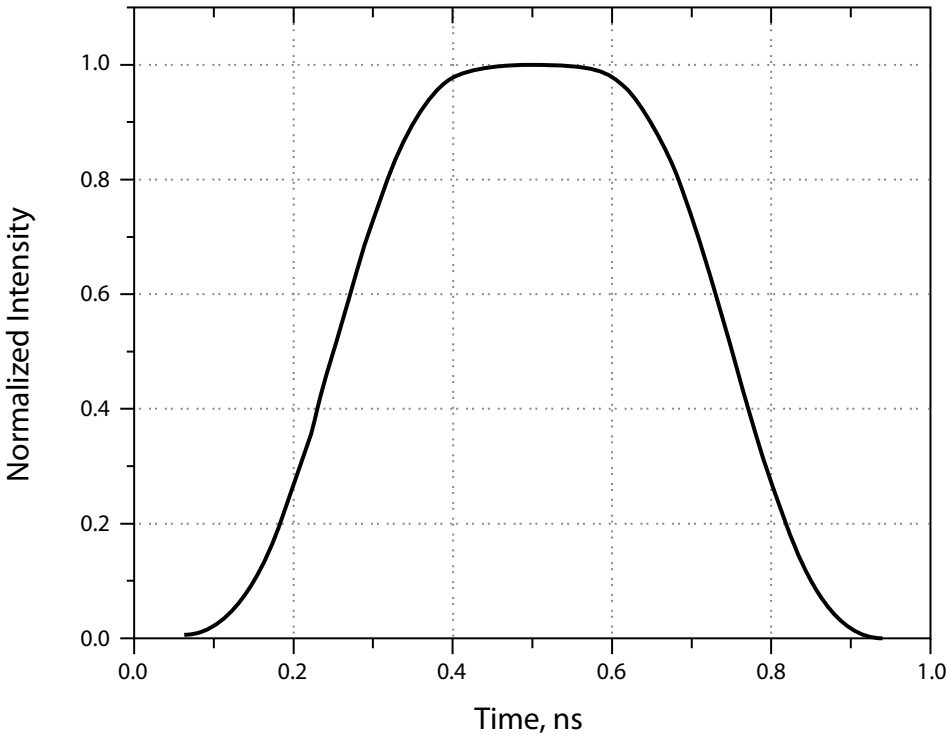

Figure 3-1: Reference Pulse Shape for f = 1 GHz

NOTE – The laser transmitter is not required to implement the exact reference pulse shape; however, transmitter implementation loss may be assessed relative to the reference waveform. Different pulse shapes can be tolerated by the receiver so long as the pulse energy is contained within the slot width and any implementation loss is accommodated by the link budget.

3.6 TIMING JITTER

The Root Mean Square (RMS) pulse timing jitter shall be less than 10 percent of the slot width, e.g., 50 picoseconds when the slot width is 0.5 ns.

3.7 SLOT WIDTH

The slot width T shall be 0.125, 0.25, 0.5, 1, 2, 4, 8, or 512 ns.

3.8 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 4 ns and as far apart as 35 ns, corresponding to a PRR range of 28 to 250 MHz.

4 HPE UPLINK SIGNAL CHARACTERISTICS

4.1 CENTER FREQUENCY

The center frequency shall be tunable to any frequency within ±26 GHz of 280.18 THz, 281.76 THz, and 291.060 THz.

NOTE – These center frequencies correspond to wavelengths in vacuum of 1070 nm, 1064 nm, and 1030 nm, respectively.

4.2 CENTER FREQUENCY TOLERANCE

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

NOTE – At a center frequency of 281.76 THz, this corresponds to a tolerance of ±0.100 nm.

4.3 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.

4.4 IN-BAND AND SPILLOVER EMISSIONS

4.4.1 GENERAL

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

4.4.2 MODULATION

4.4.2.1 Overview

Data transmission on the uplink is optional.

4.4.2.2 When Data Transmission Is Not Used

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

4.4.2.3 When Data Transmission Is Used

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

NOTE – 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.

4.4.3 PULSE SHAPE/EYE DIAGRAM

The pulse shape shall follow the description in 3.5.4.

NOTE – In addition to the flexibility regarding the pulse shape already noted in 3.5.4, this Recommended Standard can be compatible with systems using substantially narrower pulse shapes that convey additional, higher-rate uplink 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.

4.5 TIMING JITTER

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

4.6 SLOT WIDTHS

The slot width shall be 2^{16} = 65,536 ns.

5 MANAGED PARAMETERS

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

Table 5-1: Managed Parameters for HPE

Managed Parameter	Allowed Values
n, the downlink center frequency selection parameter	0 to 43
Downlink slot width	0.125, 0.25, 0.5, 1, 2, 4, 8, or 512 ns
Downlink polarized transmission	Used or Not Used
Uplink data transmission	Used or Not Used

ANNEX A

PROTOCOL IMPLEMENTATION CONFORMANCE STATEMENT (PICS) PROFORMA

(NORMATIVE)

[To be supplied.]

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 insure 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 not related to 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 circularly polarized
RMS	root mean square
RZ50	50-percent return-to-zero
TC	telecommand
TM	telemetry

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

right-hand circular polarization: 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

[D1] *Information Technology—Open Systems Interconnection—Basic Reference Model: The Basic Model*. 2nd ed. International Standard, ISO/IEC 7498-1:1994. Geneva: ISO, 1994.

[D2] *TM Space Data Link Protocol*. Issue 2. Recommendation for Space Data System Standards (Blue Book), CCSDS 132.0-B-2. Washington, D.C.: CCSDS, September 2015.

[D3] *AOS Space Data Link Protocol*. Issue 3. Recommendation for Space Data System Standards (Blue Book), CCSDS 732.0-B-3. Washington, D.C.: CCSDS, September 2015.

[D4] *TM Synchronization and Channel Coding*. Issue 2. Recommendation for Space Data System Standards (Blue Book), CCSDS 131.0-B-2. Washington, D.C.: CCSDS, August 2011.

[D5] *TC Synchronization and Channel Coding*. Issue 2. Recommendation for Space Data System Standards (Blue Book), CCSDS 231.0-B-2. Washington, D.C.: CCSDS, September 2010.

[D6] *Spectral Grids for WDM Applications: DWDM Frequency Grid*. ITU-T Recommendation G.694.1. Geneva: ITU, 2012.

[D7] B. Moision and J. Hamkins. "Coded Modulation for the Deep-Space Optical Channel: Serially Concatenated Pulse-Position Modulation." *IPN Progress Report* 42-161 (May 15, 2005).

[D8] Robert M. Gagliardi and Sherman Karp. *Optical Communications*. 2nd ed. Hoboken, New Jersey: Wiley, March 1995.

[D9] Hamid Hemmati, ed. *Deep Space Optical Communications*. Hoboken, New Jersey: Wiley, June 2006.