The Consultative Committee for Space Data Systems

Proposed Draft Recommendation for
Space Data System Standards

HIGH DATA THROUGHPUT: PHYSICAL LAYER

PROPOSED DRAFT RECOMMENDED STANDARD

CCSDS 000.0-W-0

WHITE BOOK
October 2014

AUTHORITY

Issue:	White Book, Issue 0
Date:	October 2014
Location:	Not Applicable

(WHEN THIS RECOMMENDED STANDARD IS FINALIZED, IT WILL CONTAIN THE FOLLOWING STATEMENT OF AUTHORITY:)

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This document is published and maintained by:

CCSDS Secretariat
Space Communications and Navigation Office, 7L70
Space Operations Mission Directorate
NASA Headquarters
Washington, DC 20546-0001, USA

FOREWORD

[Foreword text specific to this document goes here. The text below is boilerplate.]

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PREFACE

This document is a draft CCSDS Recommended Standard. Its 'White Book' status indicates that its contents are not stable, and several iterations resulting in substantial technical changes are likely to occur before it is considered to be sufficiently mature to be released for review by the CCSDS Agencies.

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 and Issue	Date	Status
CCSDS 000.0-W-0	[Document Title], Proposed Draft Recommended Standard, Issue 0	October 2014	Current draft

CONTENTS

Section Page

1 INTRODUCTION

1.1 PURPOSE

[Insert introductory subsections such as PURPOSE, SCOPE, APPLICABILITY, RATIONALE, etc. See CCSDS A20.0-Y-4, *CCSDS Publications Manual* (Yellow Book, Issue 4, April 2014) for the contents of section 1.]

1.2 SCOPE

This standard is intended to enable multiple vendors to provide lasercom terminals with maximum commonality and terminal interoperation whether intended for relay or user applications. It is grounded in experience derived from LCRD, and, where appropriate, leverages approaches and language developed for that effort. Open commercial standards are used to the extent possible to maximize the availability of components and test equipment.

This standard addresses optical links between two terminals, and therefore focuses on the physical and data link layers of the Open Systems Interconnect reference model. The network, transport, and application layers are outside the scope of the document; any necessary modifications to standard protocols (e.g., modifications to transport protocols to operate over high-latency satellite links) are assumed to be the responsibility of the user and are to be defined in other specification documents. Furthermore, any encryption is outside the scope of the document, and is expected to be implemented in an end-to-end fashion at higher layers.

This standard focuses on interoperability among near-Earth platforms used for a variety of applications. As such, optical technologies suitable for scaling to data rates >>1 Gbps have been adopted; photon-counting technologies that are better suited to lower data rates are not addressed. However, Ground Relay terminals could be constructed with switchable back ends to enable sharing of the optical front end between high-rate and photon-counting formats, e.g., to share ground assets between the near-Earth and deep-space communities.

In addition to this standard, it is expected that a terminal will also require a Terminal-to-Host interface control document (ICD) to address platform-specific aspects of terminal integration, including mechanical, environmental, power, and signaling interfaces. Other details such as required power levels at the free-space optical interfaces to the terminals are expected to detailed in a Terminal-to-Terminal ICD. This division of requirements is intended to ensure interoperability while allowing sufficient flexibility to adapt terminal designs to the requirements of varying platforms and applications.

1.3 APPLICABILITY

1.4 RATIONALE

1.5 DOCUMENT STRUCTURE

1.6 DEFINITIONS

In this section, several terms used in this standard are defined.

Terminal: Any lasercom terminal, regardless of the host platform.

Forward Link: A link from the Ground Network through the Relay Segment to a User Terminal.

Return Link: A link from a User Terminal through the Relay Segment to the Ground Network.

Beacon: A beam that is used to illuminate the remote terminal during the initial search stage of the acquisition sequence. It may be at the same wavelength as the transmitted communications beam, or it may be at a different wavelength; if it is at a different wavelength, it may be intensity modulated and comprised of two wavelengths designated "acquisition" and "filler." It may or may not have a larger divergence than the communications beam, which is nominally diffraction-limited; a terminal with a synthesized beacon (sometimes referred to as a "beaconless" system) may generate a beacon by rapidly scanning a communication beam.

Communications Beam: A nominally diffraction-limited beam transmitted by a terminal for the purpose of transmitting high-rate data. A communications beam may also be used for spatial acquisition, either as a synthesized beacon or, if pointing error is sufficiently small, directly.

Slot Rate: The reciprocal of the temporal spacing between the nominal centers of two adjacent optical pulses.

User Rate: The information rate available to the user at the terminal interface. The information rate does not include any overhead for channel coding, framing, or handling clock-domain boundary crossings.

Channel Rate: The rate at which symbols are transmitted, including user source data and overhead for channel coding, framing, and handling clock-domain boundary crossings. Note the term "rate" is used in the sense of the number of channel bits transmitted per second; in burst mode the symbols are transmitted in bursts at the (higher) slot rate, with gaps between the bursts.

Burst-Mode DPSK: A form of differential phase-shift keying modulation in which the slot rate is held constant and the data rate is varied by changing the number of slots that are populated with optical pulses conveying information. The pulses are gathered in bursts due to the differential nature of the phase encoding, and the bursts are separated by periods of empty slots that are a multiple of the burst length. Within the context of this standard, burst-mode DPSK includes the 1244 Mbps user data rate where every slot is filled.

Fill Frames: In burst-mode DPSK, a frame where all 64,800 payload bits have been set to zero (prior to scrambling). Fill frames are inserted between data frames periodically to allow asynchronous clock boundaries, and are dropped at each node.

Fade: A temporary reduction in optical power collected by a terminal (e.g., due to atmospheric turbulence) that reduces or disrupts communications performance but does not fall below the threshold needed to maintain spatial tracking.

Dropout: A temporary reduction in optical power collected by a terminal (e.g., due to atmospheric turbulence) that falls below the threshold needed to maintain spatial tracking .

EIRP: Effective isotropic radiated power; i.e., useful power leaving the aperture multiplied by the antenna gain. In this standard, EIRP is “clean” EIRP, where communications implementation loss has been subtracted.

Irradiance: Total optical power density within a specified bandwidth delivered to the remote terminal.

RSSI: Optical power density within a specified bandwidth delivered to the remote terminal that is useful for communication (i.e., matched to the reference waveform). RSSI equals irradiance minus the transmitter communication implementation loss.

1.7 CONVENTIONS

1.7.1 MSB/LSB TRANSMISSION

In this standard, the most significant bit (MSB) is always transmitted first, unless otherwise indicated. All binary numbers in the following descriptions are in MSB to least significant bit (LSB) order, reading from left to right.

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 Recommended Standard 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.

[Only references required for the implementation of the specification are listed in the References subsection. See CCSDS A20.0-Y-4, *CCSDS Publications Manual* (Yellow Book, Issue 4, April 2014) for additional information on this subsection.]

[1] ANSI/IEEE Standard 149-1979, “IEEE Standard Test Procedures for Antennas,” version

2 OVERVIEW

[Non-normative overview text appears in section 2. See CCSDS A20.0-Y-4, *CCSDS Publications Manual* (Yellow Book, Issue 4, April 2014) for the contents of section 2.]

2.1 ARCHITECTURE AND INTERFACES

2.1.1 LINK SCENARIOS

The architecture supported by this standard is shown in Figure 2-1

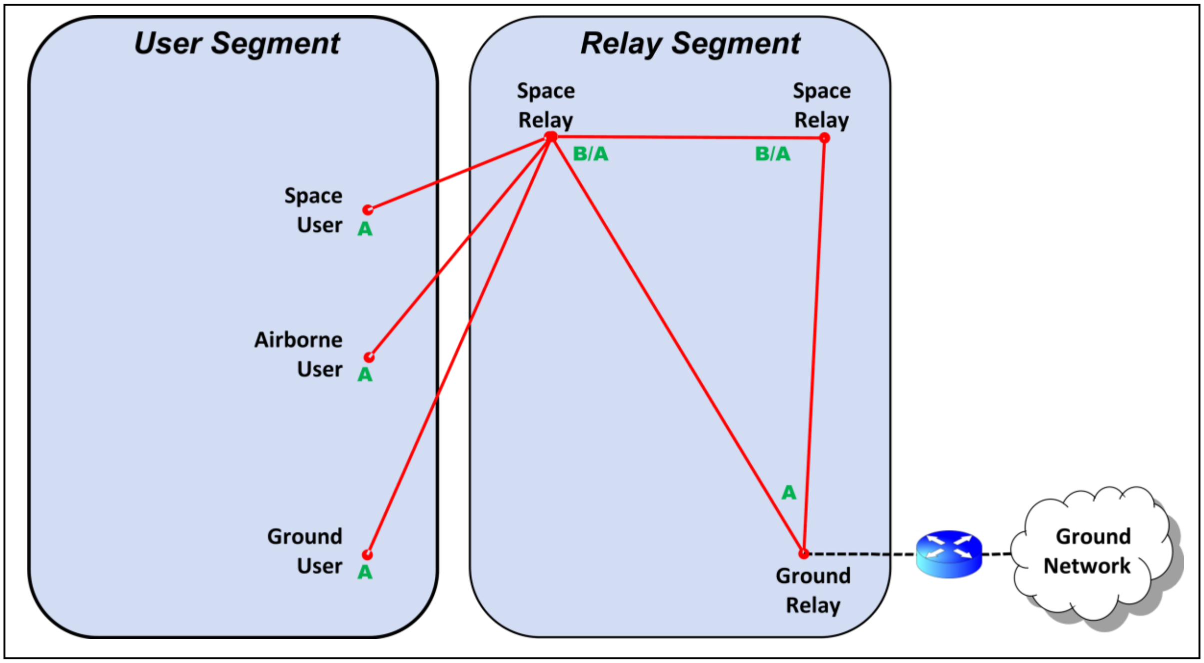

Figure 2-1. Link Architecture

The architecture is divided into a User Segment and a Relay Segment. User terminals may be hosted on space-based, airborne, or ground-based platforms. The Relay Segment includes space-based and ground-based terminals, and exists to transport data between users at the edge of a network and ground-based networks; Ground Relay terminals serve as gateways to the ground-based networks. Space Relay terminals are assumed to be in geosynchronous orbits .

Terminals are designated either Type A or Type B, which has implications for the wavelength plan, polarization plan, and acquisition sequence. Type A terminals can only interoperate with Type B terminals, and vice versa. Platforms with multiple terminals may incorporate a mix of Type A and Type B terminals; alternatively, they may incorporate terminals that are switchable between Type A and Type B. Multi-hop links are straightforward extensions of the single-hop links shown; for example, data may be transferred from a Type A airborne User Terminal to a Type B Space Relay terminal via an uplink, then from a Type A Space

Relay terminal to a Type B Space Relay terminal via a crosslink, and finally from a Type B Space Relay terminal to a Type A Ground Relay terminal via a downlink.

Terminals are further designated Type 1 or Type 2 based on whether they used distinct acquisition wavelengths or use the communications wavelength for acquisition; thus there are four distinct terminal types defined: A1, B1, A2, and B2. Further details are provided in section 4.1.

2.1.2 LINK SCHEDULING AND MANAGEMENT

The following assumptions are made about establishing service:

1) The links are coordinated by an external entity. Links may either be prescheduled or initiated by commands in near-real-time.

2) If the link is prescheduled, the terminal's host must provide it with the location and velocity information for the remote terminal to the accuracies specified in the relevant interface control or other system specification documents. If the link is to be established in near-real-time or updated after a mission begins, the host platform must have an out-of-band command link that can be used to provide the remote terminal information.

With the exception of the time to initiate contact and the location and velocity of the remote terminal, the details of establishing service are outside the scope of this standard. For example, these might include mission scheduling, resource prioritization and de-confliction, platform CONOPS, authentication algorithms, and the assignment and distribution of unique words (defined in section 4.4.3).

2.1.3 DATA PROCESSING OVERVIEW

2.1.3.1 Processing Sequence

This specifies burst-mode links for user data rates up to ~1 Gbps. Burst-mode links use a custom, asynchronous physical layer frame structure. Fill frames are used to achieve the asynchronous clock boundaries throughout the links. A Unique Word in the frame header is used to distinguish between user data and fill frames. Space Relay command and telemetry streams may also be defined with their own Unique Words.

Data flowing from a User Terminal arrives as link-layer frames (e.g., Ethernet frames or CCSDS transfer frames), with details defined in the Terminal-to-Host ICD. The system transparently bridges these frames to the Ground Relay. The Ground Relay may then forward frames to the terrestrial link-layer interface.

Data flowing to a User Terminal arrives from the terrestrial network as link-layer frames (e.g., Ethernet frames or CCSDS transfer frames). The system transparently bridges these frames to the User Terminal. The link-layer frames are passed to the user platform, with details defined in the Terminal-to-Host ICD.

To be compatible with the overall network architecture, the edge-to-edge connectivity operates with several constraints. Figure 2-2 illustrates the network protocol stacks and link-layer bridging through the system.

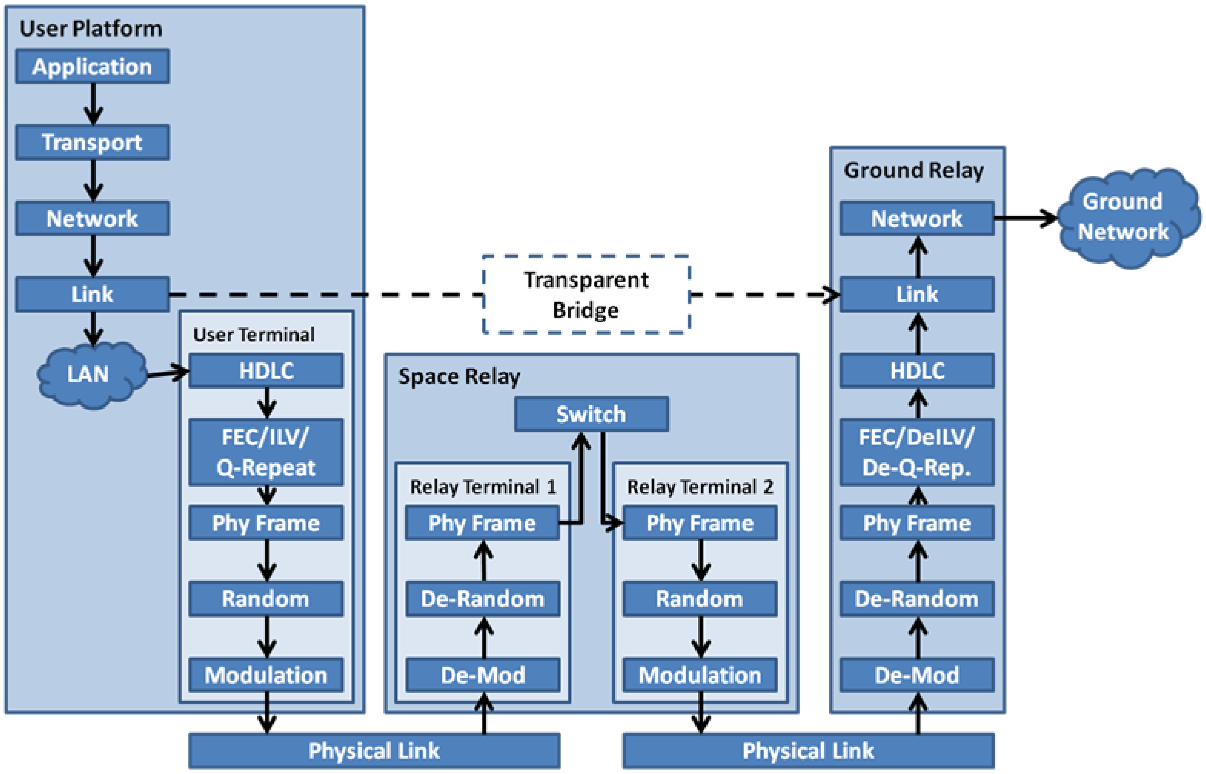

Figure 2-2. Link Example

In order to move data through the system, the data must be framed at each node. For burst-mode links, data to be transmitted is presented to the terminal at a link layer (e.g. Ethernet) interface. The data is processed in the following sequence:

- Bursty input data is converted to constant bit rate using HDLC
- Error correction coding is applied
- Interleaving is applied (if appropriate for the channel)
- The (interleaved) codewords are Q-repeated (if needed) and multiplexed
- The Q-repeated codewords are encapsulated into frames and headers are added.
- The frames are randomized (at the slot level)
- The scrambled frames are modulated onto an optical carrier and transmitted over the link

At the receiver, the scrambled frames are demodulated and the sequence is then reversed.

2.1.3.2 Full vs. Partial Processing

For burst-mode links, this standard supports both full and partial processing aboard a given platform for multi-hop links, as illustrated in Figure 2-2. Here, full processing refers to demodulating, derandomizing, removing fill frames (if present), processing the frame headers, deinterleaving (if needed), and decoding the transmitted data and then repeating the entire processing chain for transmission over the next hop. Partial processing refers to demodulating the incoming data, derandomizing, removing the fill frames, and processing headers, but not deinterleaving or decoding. In this case, new frame headers are applied and the transmit processing chain resumes from there.

2.1.3.3 Data Rate Modes

This standard supports the modes defined in Table 2-1. The rates in Table 2-1 represent nominal baseband data rates available to the user. Any encryption or other overhead added by the user will reduce these data rates, but overhead due to encapsulation, coding, and physical layer framing as defined in this standard is already accounted for.

Table 2-1. Data Rate Modes

Mode Name	User Data Rate (Mbps)	Q Repetition	Channel Rate (Mcbps)
U-1244	1244 (Max)	1	2880
U-622	622 (Max/2)	1	1440
U-311	311 (Max/4)	1	720
U-155	155.5 (Max/8)	1	360
U-51.8	51.8 (Max/24)	1	
U-16	16	2	72
U-8	8	4	72
U-4	4	8	72
U-2	2	16	72

The user rates shown in Table 2-1 assume the nominal rate-1/2 coding. In links that are only partially processed in the Space Relay(s), other code rates may be implemented with different amounts of coding gain and overhead if coordinated with the Ground Relay.

The Space Relay to Ground Relay interface may include logical interface that carries a command stream from the Ground Relay to the Space Relay and a telemetry stream from the Space Relay to the Ground Relay. The Space Relay command stream is handled in the same way as a User data stream, with the exceptions that the Space Relay command stream terminates in a Space Relay rather than a User Terminal.

The Space Relay command stream contains command frames for the Space Relay terminal that the Ground Relay receives from the ground network. The Space Relay command frames are assigned a unique word that is not assigned to any other frames in the system. These frames are sent to the Space Relay through the appropriate interfaces from the ground terminal. The Space Relay then performs the receive processing and then processes the commands.

The Space Relay telemetry stream is handled in the same way as a User data stream, with the exceptions that the Space Relay telemetry data originates in the Space Relay rather than a User Terminal.

The Space Relay telemetry contains telemetry generated by the Space Relay terminal. The Space Relay telemetry frames are assigned a unique word that is not assigned to any other frames in the system. These frames are sent from the Space Relay through the appropriate interfaces to the Ground Relay. The Ground Relay then performs the receive processing and sends the Space relay telemetry to the ground network.

2.1.4 SCINTILLATION MITIGATION

A variety of techniques have been developed to mitigate the scintillation affects associated with atmospheric turbulence and residual dynamic pointing and tracking errors. These include network-based retransmission protocols, adaptive optics, techniques based on channel reciprocity, spatial diversity receivers and transmitters, and forward error correction coding augmented with data interleaving. Retransmission protocols are addressed at the transport layer and are outside the scope of this standard. Adaptive-optic techniques, reciprocity techniques, and spatial diversity receivers can be implemented at one end of a link without affecting the design of the remote terminal, and therefore are not explicitly addressed in this standard; any (or none) of these techniques can be used in a compliant terminal. Spatial diversity transmitters, however, have wavelength requirements that affect both ends of the link, and are discussed below in the wavelength plan*. Likewise, the coding and interleaving choices must be coordinated between both ends of a link, and are covered below in sections 4.2 and 4.3.

* *As of this draft, support for multi-wavelength diversity transmitters is being considered, but has not yet been incorporated.*

2.1.5 ACCOMMODATION OF DOPPLER SHIFT

The approach to accommodating Doppler shift in links within the architecture is as follows:

Both User Terminals and Relay Terminals will have sufficient locking bandwidth in their clock recovery subsystems to accommodate Doppler shift of the slot rate as well as a specified amount of residual variation (long-term drift) of the remote terminal’s transmitter clock.

User Terminals and Ground Relay Terminals will pre-compensate the center frequency of their optical carrier such that it will be within the required accuracy in the frame of reference of the Space Relay. This pre-compensation requires knowledge of both the local terminal's position and velocity and the Space Relay terminal's position and velocity (i.e., ephemeris).

3 SPATIAL ACQUISITION

[Normative specifications appear in sections 3 through *n*. See CCSDS A20.0-Y-4, *CCSDS Publications Manual* (Yellow Book, Issue 4, April 2014).

All sections and annexes should be separated by Word continuous section breaks.]

3.1 ACQUISITION SEQUENCE

3.2 ACQUISITION TIME

3.3 TERMINAL A

3.3.1 CENTER FREQUENCIES

3.3.1.1 Laser Tuning Range

3.3.1.2 Laser Tuning Range Rate

3.3.1.3 Laser Line Width

3.3.1.4 Laser Relative Intensity Noise

3.3.1.5 Laser Frequency Noise

3.3.1.6 Laser Phase Noise

3.3.2 POLARIZATION

3.3.2.1 Polarization Type

3.3.2.2 Polarization Extinction Ratio

3.3.3 MODULATION

3.3.3.1 Modulation Scheme

3.3.3.2 Spectral Mask

3.3.3.3 Pulse Shape

3.3.3.4 Pulse Repetition Rate

3.3.3.5 Extinction Ratio

3.4 TERMINAL B

3.4.1 CENTER FREQUENCIES

3.4.1.1 Laser Tuning Range

3.4.1.2 Laser Tuning Range Rate

3.4.1.3 Laser Line Width

3.4.1.4 Laser Relative Intensity Noise

3.4.1.5 Laser Frequency Noise

3.4.1.6 Laser Phase Noise

3.4.2 POLARIZATION

3.4.2.1 Polarization Type

3.4.2.2 Polarization Extinction Ratio

3.4.3 MODULATION

3.4.3.1 Modulation Scheme

3.4.3.2 Spectral Mask

3.4.3.3 Pulse Shape

3.4.3.4 Pulse Repetition Rate

3.4.3.5 Extinction Ratio

4 COMMUNICATIONS SIGNAL

4.1 BAND PLAN

This section defines the wavelengths used in the standard, which correspond to the center frequency of the optical carrier. All wavelengths are specified in terms of the vacuum wavelength, related to the center carrier frequency via $\lambda = c/\nu$, where c is the speed of light in a vacuum and ν is the carrier frequency. Depending on the context, requirements are specified in terms of either wavelength or frequency.

Type A terminals shall receive a communications signal on λ_1 and transmit their communications signal on λ_2.

Type B terminals shall transmit their communications signal on λ_1 and receive a communications signal on λ_2.

Type 1 terminals shall transmit (Type A) or receive (Type B) a beacon that is distinct from the communications wavelength, comprised of an optional filler signal on λ_3 and an acquisition signal on λ_4.

Wavelengths λ_1, λ_2, λ_3, and λ_4 shall be chosen from the 50-GHz (TBR) DWDM grid from 191.50 THz (TBR) to 195.90 THz (TBR) specified in ITU-T G.694.1 (02/2012).

For the purpose of preserving the low-frequency acquisition modulation through the high-pass filtering effects of a saturated high-power optical amplifier, the terminal may emit a filler beam that is intensity modulated with the complement of the modulation that is applied to the acquisition beam (as specified in Table TBS).

Note: The combination of the filler and acquisition wavelengths maintains an effectively constant input power to the high-power optical amplifier, minimizing effects related to gain dynamics. The two wavelengths co-propagate through the channel, and the filler wavelength is rejected by a filter in the remote terminal. The power in the filler wavelength is not counted towards any EIRP values specified in Table TBS or any delivered power density values specified in Tables TBS.

Type 2 terminals shall use their communications wavelengths for acquisition , i.e., they will have one transmit wavelength and one receive wavelength.

Thus, as shown in Table 4-1, a Type A1 terminal receives a communications signal on λ_1 and transmits a communications beam on λ_2 as well as a beacon with a filler signal on λ_3 and an acquisition signal on λ_4. A Type B1 terminal transmits a communications beam on λ_1 and receives a communications signal on λ_2, a filler signal on λ_3, and an acquisition signal on λ_4. A Type A2 terminal transmits both its beacon and communications signal on λ_2 and receives on λ_1, and a Type B2 terminal transmits both its beacon and communications signal on λ_1 and receives on λ_2.

Table 4-1. Wavelength Plan

Terminal Type	Tx Acq	Tx Fill	Tx Comm	Rx Acq	Rx Comm
A1	λ_4	λ_3	λ_2	λ_1	λ_1
B1	λ_1	**N/A**	λ_1	λ_4	λ_2
A2	λ_2	**N/A**	λ_2	λ_1	λ_1
B2	λ_1	**N/A**	λ_1	λ_2	λ_2

4.1.1 CHANNELIZATION

4.1.2 INTERCHANNEL INTERFERENCE/ISOLATION

4.2 TERMINAL A

4.2.1 CENTER FREQUENCIES

Doppler Accommodation

In order to compensate for Doppler frequency shifts due to relative line-of-sight motion between terminals, all terminals except Space Relays are required to pre-tune the center frequency of their transmitted communications beam. Terminals are not required to Doppler pre-compensate either the acquisition or filler beams, but may do so if desired. Space Relay terminals are not required to Doppler pre-compensate their communications beams.

System errors present in the estimation of relative velocity and/or frequency, including satellite ephemeris errors, lead to frequency errors even after Doppler compensation. A terminal is only required to compensate for frequency errors within its control and is not required to compensate for errors outside of its control, e.g., errors caused by inaccurate position and velocity information for the remote terminal.

In a link between a User Terminal and a Space Relay, the User Terminal shall tune its transmitter communication wavelength to pre-compensate for Doppler shift to the accuracy specified in section 4.2.1.

In a link between a User Terminal and a Space Relay, the User Terminal shall accommodate the Doppler shift in its received communication wavelength.

In a link between a Ground Relay and a Space Relay, the Ground Relay shall tune its transmitter communication wavelength to pre-compensate for Doppler shift to the accuracy specified in section 4.2.1.

In a link between a Ground Relay and a Space Relay, the Ground Relay shall accommodate the Doppler shift in its received communication wavelength.

Note: A terminal may accommodate the Doppler shift in its receive wavelength by tuning its receiver or by incorporating link margin to accommodate the power penalty.

Accuracy

After accounting for Doppler shift, drift, and calibration error, the center frequency of a terminal's acquisition beam shall be within ±20 GHz of the specified frequencies with a probability ≥99.7%.

After accounting for Doppler shift, drift, and calibration error, the center frequency of a terminal's filler beam (if present) shall be within ±20 GHz of the specified frequencies with a probability ≥99.7%.

After accounting for Doppler pre-compensation, drift, and calibration error, the center frequency of the terminal's comm beam shall be within ±100 MHz of the specified frequencies with a probability ≥99.7%.

Tunability

Ground User terminals shall be able to tune the center frequency of their communications beam by up to ±50 MHz at rates up to ±5 MHz/s.

Airborne User terminals shall be able to tune the center frequency of their communications beam by up to ±300 MHz at rates up to ±10 MHz/s.

Space User terminals shall be able to tune the center frequency of their communications beam at magnitudes and rates commensurate with the orbit of their host platform.

Ground Relay terminals shall be able to tune the center frequency of their communications beam by up to ±50 MHz at rates up to ±5 MHz/s.

4.2.1.1 Laser Tuning Range

4.2.1.2 Laser Tuning Range Rate

4.2.1.3 Laser Line Width

If the modulation format for the link is DPSK, the full-width at half-maximum linewidth of the unmodulated master oscillator laser for communication shall be less than 10 MHz (TBR).

Note: The intent of this requirement is to ensure that the communications implementation loss caused by linewidth is negligible and to allow the option for a coherent receiver architecture.

4.2.1.4 Laser Relative Intensity Noise

4.2.1.5 Laser Frequency Noise

Absent Doppler pre-compensation, the average center frequency of a terminal’s comm beam shall not vary by more than 50 MHz in one second in the terminal’s local frame of reference.

Note: Dithering of the center frequency is allowed so long as the dither excursion is within the frequency accuracy requirement and the average frequency meets the stability requirement.

4.2.1.6 Laser Phase Noise

4.2.1.7 In-Band and Spillover Emissions

Wavelengths emitted by a Type A1 terminal shall conform to the in-band and spillover radiated emissions specifications in Table 4-2. Figure 4-1notionally illustrates the various in-band and spillover spectral regions that are the subject of these specifications.

The in-band limits define the spectral region over which a Type A1 terminal’s effective isotropic radiated power (EIRP) and the delivered irradiance are calculated. These are determined separately at each of the wavelengths transmitted by the Type A1 terminal: communications ($\lambda_C = \lambda_2$), filler ($\lambda_F = \lambda_3$), and acquisition ($\lambda_A = \lambda_4$).

For Type A1 terminals, the in-band spectral limits shall be ±20 GHz relative to the nominal center wavelengths.

Spurious spillover radiation generated by a Type A1 transmitter at any one or more of the three wavelengths (λ_C, λ_F, or λ_A) that falls into one or more of the pass bands of the Type B1 receiver may degrade that receiver's performance.

The spillover limits are used to calculate the maximum amount of allowable "spillover" irradiance delivered at the Type B1 terminal input aperture.

For Type A1 terminals, the spillover spectral limits shall be ±50 GHz relative to the nominal center wavelengths.

Four separate spillover scenarios are depicted in Figure 4-1: (1) spillover from λ_F into λ_C, (2) from λ_A into λ_C, (3) from λ_F into λ_A, and (4) from λ_C into λ_A. Note that spillover into λ_F is not considered because there is no receiver operating at that particular wavelength. For the purposes of specifying spillover limits, it is the total spillover irradiance from all transmitted wavelengths that must meet the spillover specifications at any one receiver channel. In other words, when considering spillover into λ_C, the total contributions, i.e., the sum, of spillover emissions from λ_F and λ_A must meet the specification (as shown in Table 4-2). Likewise, when considering spillover into λ_A, the total contributions, i.e., sum, of spillover emissions from λ_F and λ_C must meet the specification (as shown in Table 4-2).

Table 4-2. Terminal Type A1 Spillover Specifications

Item	Item Description	Specification
1+2	Maximum allowable spillover into communication band in relay aperture plane(1)	Min RSSI - 20 dB(2)
3+4	Maximum allowable spillover into acquisition band in relay aperture plane(3)	**TBS** nW/m^2

Notes:

1) Maximum instantaneous sum of all spillover contributions, i.e., from both the acquisition and filler wavelengths (items 1 and 2 in Fig SPILL), that fall within the spillover limits of the communications wavelength
2) Power density value specified here is 20 dB below the min RSSI value for the intended data rate
3) Maximum instantaneous sum of all spillover contributions, i.e., from both the communications and filler wavelengths (items 3 and 4 in Fig SPILL), that fall within the spillover limits of the acquisition wavelength

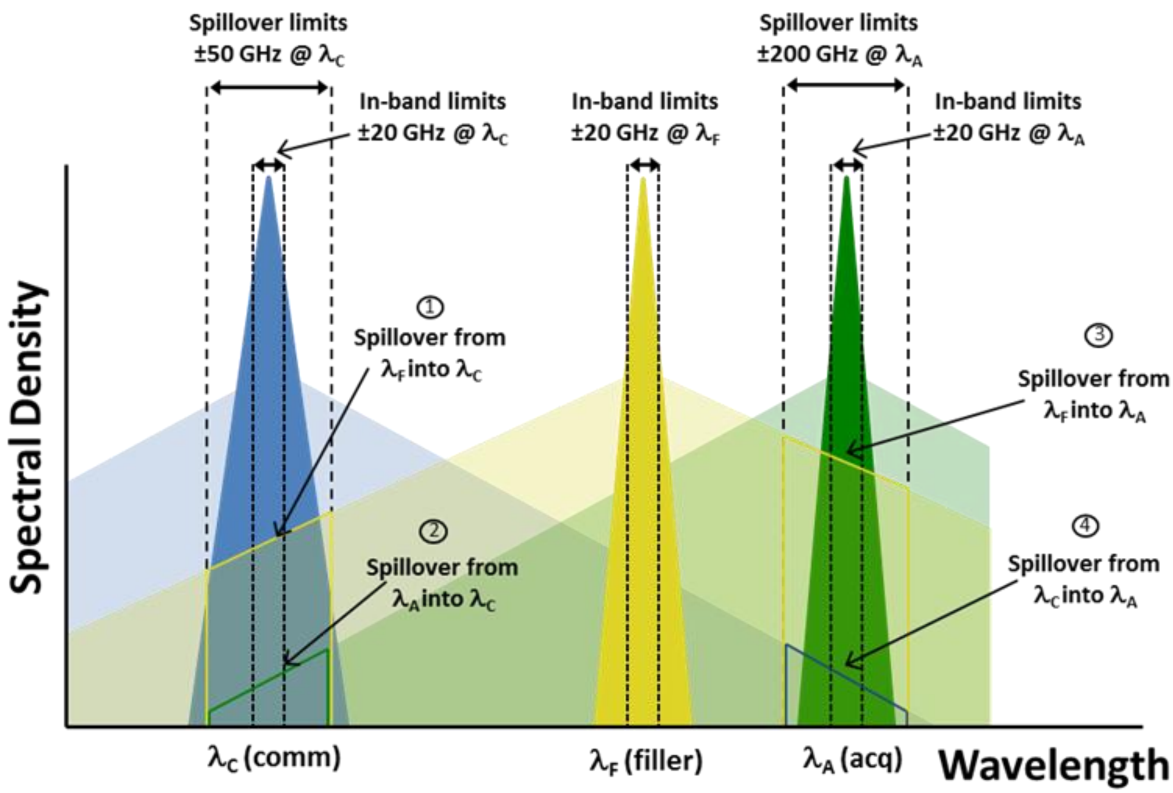

Figure 4-1. Spillover definitions

4.2.2 POLARIZATION

4.2.2.1 Polarization Type

The polarization state of beams transmitted by a Type A terminal shall be right-hand circular as defined by ANSI/IEEE Standard 149-1979, "IEEE Standard Test Procedures for Antennas." [1]

4.2.2.2 Polarization Extinction Ratio

The magnitude of the degree of circular polarization (DOCP) of a beam transmitted by a terminal shall be at least 90% (i.e., $|S3|/S0 \geq 0.90$, where S3 and S0 are Stokes parameters.)

Note: Only power delivered in the specified polarization state and within a specified optical bandwidth is counted towards terminal EIRP and delivered irradiance.

Note: The terminal's transmit path may be implemented with passive polarization-maintained components or with active polarization control. The terminal's receive path may be implemented with a polarization-maintained, polarization-controlled, or nominally polarization-independent path.

4.2.3 MODULATION

4.2.3.1 Modulation Scheme

For the 2880 MHz slot rate, the communications beam transmitted by a terminal shall be modulated with burst-mode (defined in section 4.2.3.1) differential phase-shift keying (DPSK).

For the communications beam transmitted by a terminal, the applied DPSK modulation shall have a phase change between successive pulses of 0 radians for a binary '0' channel bit and π radians for a binary '1' channel bit.

For burst-mode links, the physical layer format used by both terminals in a link shall consist of bursts of DPSK optical pulses in slots that occur at 2.88 GHz. This is referred to as burst-mode DPSK.

The various fields of a physical layer burst-mode frame are described in section 4.4. Specifically, a physical layer frame consists of 1024 header bits and 64800 codeword bits. The 64800 codeword bits are encoded and interleaved data bits as described in sections 4.2 and 4.3, respectively.

For each physical layer frame generated by a terminal on a burst-mode link, the header and codeword bits shall be distributed into bursts of 176 slots filled with data followed by Dx176 slots of off-time as shown in Figure 4-2.

Note: Each physical layer frame consists of 374 bursts of 176 bits (374 x 176 = 1024 + 64800), and the data rate is varied by changing the amount of off-time between the bursts.

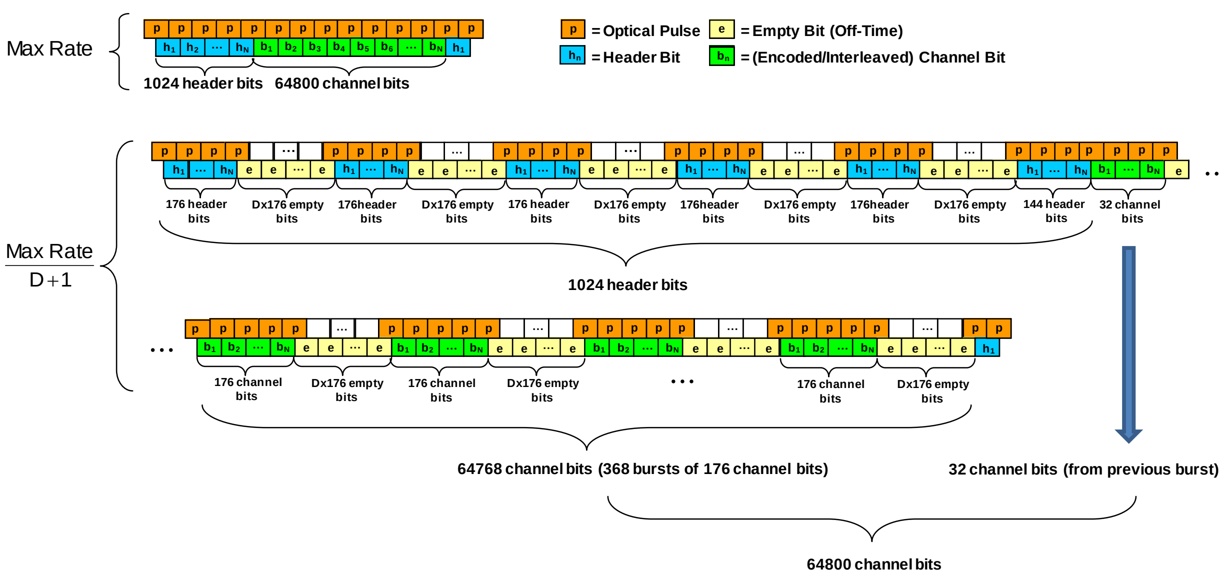

Figure 4-2. Physical Layer Burst-Mode Format

The values of D for each physical layer frame shall be as shown in Table 4-3 for the various user data rates on the burst-mode link.

As the link data rate decreases, an increasingly longer amount of off-time is inserted between bursts of pulses. Because a physical layer frame always contains 1024 header bits and 64800 channel bits, the physical layer frame duration increases as the link data rate decreases.

At the maximum rate (U-1244), D is zero and every slot contains an optical pulse. At rates less than the maximum rate (i.e., rates where off-time is incorporated using a non-zero value for D), an additional optical pulse is required at the end of each off-time period due to the DPSK modulation format. This requires transmission of 177 pulses for every 176 bits, requiring transmission of an extra 0.025 dB optical power (which is included in the receiver communications implementation loss as discussed in section 4.2.3.7). Because this additional pulse carries no information, it is treated as part of the off-time between data bursts.

Table 4-3. Frame Parameters for a Burst-Mode Link

Link Data Rate (Mbps)	**Mode Name**	**D**	**Q**	**Data Burst Time (ns)**	**Off-Time (ns)**	**Frame Length (μs)**
1244 (Max)	U-1244	0	1	61.111	0.000	22.856
622 (Max/2)	U-622	1	1	61.111	61.111	45.711
311 (Max/4)	U-311	3	1	61.111	183.333	91.422
155.5 (Max/8)	U-155	7	1	61.111	427.778	182.844
51.8 (Max/24)	U-51.8	23	1	61.111	1405.556	548.533
16	U-16	39	2	61.111	2383.333	914.222
8	U-8	39	4	61.111	2383.333	914.222
4	U-4	39	8	61.111	2383.333	914.222
2	U-2	39	16	61.111	2383.333	914.222

For nominal user data rates below 51.8 Mbps (i.e., U-16 modes and lower), the off-time and frame length are fixed and lower data rates are achieved via repetition of physical layer frames. Off-time and frame length do not change with Q, but the effective data rate available on the link drops accordingly.

4.2.3.1.1 Symbol Synchronization, if applicable

4.2.3.2 Spectral Mask

4.2.3.3 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% return-to-zero (RZ50) waveform defined by

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

where

$$V(t) = \frac{V_\pi}{4}\cos(2\pi f t)$$

V_π is the voltage required to induce a pi phase shift in the modulator, and f = 1/T is the slot rate. The reference pulse shape for a slot rate of 2.88 GHz is shown in Figure 4-3.

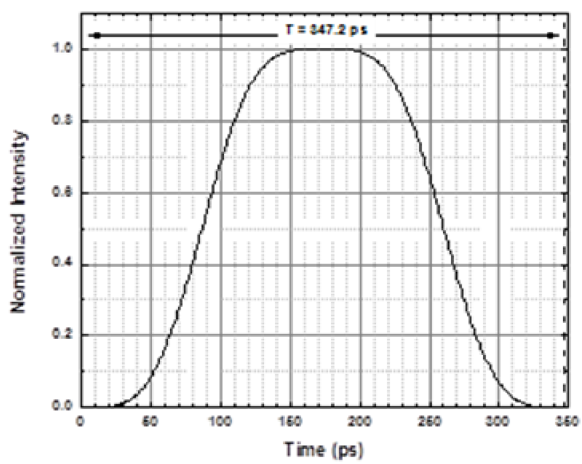

Figure 4-3. Reference Pulse Shape for f = 2.88 GHz

The reference optical waveform shall be chirp-free, exclusive of the phase encoding of the DPSK signal (i.e., at the bit transition points).

Note: The chirp-free reference pulse shape illustrated in Figure 4-3 can be produced with a zero-chirp push-pull or X-cut Mach-Zehnder interferometric modulator biased at quadrature and driven with a sinusoidal voltage at the slot rate.

Note: A terminal is not required to implement the exact reference pulse shape; however, transmitter implementation loss is assessed relative to the reference waveform, and communications performance requirements are defined relative to the reference waveform. Different pulse shapes can be tolerated by the receiver so long as the implementation loss is accommodated by the link budget and all waveform quality metric requirements are met. See also the waveform quality requirements in section 4.2.3.7.

4.2.3.4 Pulse Repetition Rate(s)

The slot rate is the maximum rate at which optical pulses can be transmitted. In burst mode, some slots are occupied by pulses and others are nominally empty. A pulse is a symbol and may represent source information, overhead for error correction coding, or frame header information.

Burst-mode links shall use the 2.88 GHz slot rate.

4.2.3.4.1 Accuracy and Stability

A terminal's transmitter must transmit an optical signal with phase stability compatible with the remote terminal receiver. The remote terminal receiver first acquires a slot clock from the optical signal, and then acquires frame synchronization. If the modulation format is burst-mode DPSK, frame sync provides synchronization to both the burst-mode optical format and the physical layer framing, as described in sections 4.2.3.1 and 4.4, respectively.

The receiver tracking-loop bandwidth should be selected to be slow enough to free-run through dropouts. This requires that the transmitter phase stability is such that the clock does not drift by a significant fraction of a slot during the characteristic phase-locked loop lock-up time.

The nominal slot rate of the communications beam transmitted by a terminal shall be one of the rates defined in section 4.2.3.4 in the terminal's frame of reference.

Note: One slot width is the reciprocal of the slot rate, and only one optical pulse occurs per slot.

A terminal's transmitter clock phase noise shall be such that the timing jitter induced by integrated phase noise above 10 Hz (TBR) is less than 5% (TBR) of a nominal slot period (e.g., <17 ps for the 347 ps slot associated with the 2880 MHz slot rate).

For similar phase-stability reasons, the jitter of a terminal's transmitter line-of-sight motion shall not exceed 5% (TBR) of a slot length (e.g., (3E8 m/s)/2.880GHz = 10.4 cm) at frequencies above 10 Hz (TBR).

Note: Depending on the host platform's vibration environment, this requirement may imply the need for vibration isolation to be incorporated into the terminal.

The transmitter clock frequency of a Space Relay terminal shall be within ±10 ppm (TBR) of the nominal slot rate.

The transmitter clock frequency of a User Segment or Ground Relay terminal shall be within ±10 ppm (TBR) of the nominal slot rate.

A terminal's receiver shall be able to synchronize to the remote terminal's transmitter slot rate accounting for both Doppler shift and remote terminal transmitter clock drift.

4.2.3.5 Extinction Ratio

4.2.3.6 data Rates (Range of Rates, Discrete Set, etc.)

4.2.3.7 Waveform Quality Metrics

A terminal's transmitter communications loss shall not exceed 3.0 dB.

Sources of transmitter communications implementation loss include, but are not necessarily limited to:

1. Waveform penalty (as defined in Appendices C and D)

Note: The procedure in Appendix D evaluates waveform penalty performance of the implemented transmitter waveform with an ideal realization of the receiver matched to the nominal waveform.

While not needed for the purposes of the interface definition, note that potential contributions to receiver communications implementation loss include but are not limited to:

1. Optical background (from both natural sources and local transmitter amplified spontaneous emissions coupled into the receiver);

2. Losses in the receiver fiber prior to the optical low-noise amplifier (OLNA);

3. The excess noise figure of the OLNA;

4. The penalty for the second polarization of amplified spontaneous emissions in the OLNA;

5. Local wavelength misalignments between the optical filters and the DPSK demodulator;

6. Local wavelength misalignments of any other receiver component from the nominal wavelength;

7. Amplitude imbalance between balanced DPSK photodetectors;

8. The extra pulse required for burst-mode DPSK (as defined in section 4.2.3.1).

These are all factors that reduce the achievable receiver sensitivity, which is defined at the input to the fiber receiver (power coupled into fiber).

For burst-mode links, the transmitter extinction ratio for a terminal’s communications beams shall be at least 18 dB (TBR).

Note: For the purposes of this standard, the transmitter extinction ratio is defined as the ratio of the average energy per slot for slots occupied by pulses to the average energy per slot for slots not occupied by pulses.

The optical signal-to-noise ratio (OSNR) of the modulated communications beam transmitted by a terminal shall exceed 30dB (TBR) as measured over a bandwidth defined by the measured communications center frequency ±50 GHz (TBR) with a resolution bandwidth of 0.1 nm.

The clock-to-average power ratio (CAPR) of the modulated communications beam transmitted by a terminal shall exceed -4.0 dB (TBR) as defined in Appendix E.

4.3 TERMINAL B

4.3.1 CENTER FREQUENCIES

4.3.1.1 Laser Tuning Range

4.3.1.2 Laser Tuning Range Rate

4.3.1.3 Laser Line Width

4.3.1.4 Laser Relative Intensity Noise

4.3.1.5 Laser Frequency Noise

4.3.1.6 Laser Phase Noise

4.3.2 POLARIZATION

4.3.2.1 Polarization Type

The polarization state of beams transmitted by a Type B terminal shall be left-hand circular as defined by ANSI/IEEE Standard 149-1979, “IEEE Standard Test Procedures for Antennas.” [1]

4.3.2.2 Polarization Extinction Ratio

4.3.3 MODULATION

4.3.3.1 Modulation Scheme

4.3.3.1.1 Symbol Synchronization, if applicable

4.3.3.2 Spectral Mask

4.3.3.3 Pulse Shape/Eye Diagram

4.3.3.4 Pulse Repetition Rate(s)

4.3.3.4.1 Accuracy and Stability

4.3.3.5 Extinction Ratio

4.3.3.6 Data Rates (Range of Rates, Discrete Set, etc.)

5 RANGING

ANNEX A

[ANNEX TITLE]

[EITHER NORMATIVE OR INFORMATIVE]

[Annexes contain ancillary information. Normative annexes precede informative annexes. Informative references are placed in an informative annex. See CCSDS A20.0-Y-4, *CCSDS Publications Manual* (Yellow Book, Issue 4, April 2014) for discussion of the kinds of material contained in annexes.]

ANNEX B

SECURITY

(INFORMATIVE)

B1 INTRODUCTION

B2 SECURITY CONCERNS WITH RESPECT TO THE CCSDS DOCUMENT

B2.1 DATA PRIVACY

B2.2 DATA INTEGRITY

B2.3 AUTHENTICATION OF COMMUNICATING ENTITIES

B2.4 CONTROL OF ACCESS TO RESOURCES

B2.5 AVAILABILITY OF RESOURCES

B2.6 AUDITING OF RESOURCE USAGE

B3 POTENTIAL THREATS AND ATTACK SCENARIOS

B4 CONSEQUENCES OF NOT APPLYING SECURITY TO THE TECHNOLOGY