POLITECNICO DI TORINO

Master's Degree in
Communication and Computer Networks Engineering

Master's Degree Thesis

Design and Validation of a Multi-User Architecture and Multiplexing Techniques for Lunar Proximity Communication Links

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Abstract

This thesis proposes the design of a multi-user architecture for Lunar proximity communication links, with a focus on Data Link Layer and Physical Layer multiplexing techniques. The core of the work is the design and validation of the strategies adopted at the Physical Layer. The study is part of ANDROMEDA, a Lunar communication service based on a constellation of microsatellites designed by the Italian aerospace company *Argotec*.
After a brief description of ANDROMEDA's baseline architecture and concept of operations, the definition of system requirements to support multi-user communications follows. The protocol stack is then defined with a description of involved Consultative Committee for Space Data System (CCSDS) Standards and a couple of use cases are also presented.
The main guidelines for the development of the work have been the Space Frequency Coordination Group (SFCG) frequency allocation recommendation for the Lunar region, the Future Lunar Communication Architecture document released by the Interagency Operations Advisory Group (IOAG), and especially the Draft LunaNet Interoperability Specification written by NASA Goddard Space Flight Center in cooperation with ESA. All of them give essential information for the protocol stack trade-off analysis and the subsequent Data Link Layer study. Based on it, the multiplexing processes of the Data Link Layer are defined.
Following a brief discussion about working frequencies and modulations, the multiplexing stage at the Physical Layer is realized by means of a synthesizer and its description and working parameters are provided.
The document ends with the description of the tests conducted to validate the system following the realization of a dedicated software in *C++*. Tests were carried out exploiting a Software Defined Radio (SDR) and a spectrum analyzer was used to collect results. The latter have demonstrated the architecture feasibility.

Acknowledgements

The master's degree in Communication and Computer Networks marked a turning point in my life. It has made me passionate about studying the subjects offered, to study them in depth, to commit myself fully, and to believe in my abilities. My interest in the topics covered by the course was not the only reason I am grateful to have embarked on this course of study. Great credit is mainly due to the professors who were true reference points and managed, despite the difficulties due to the pandemic, to make the lectures interesting and lively.
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Table of Contents

List of Tables

List of Figures

Acronyms

3GPP 3rd Generation Partnership Project.

ANDROMEDA Argotec Network Design for Real-time Operations in Moon Environment and Deep-space Applications.

AOS Advanced Orbiting System.

AR4JA Accumulate, Repeat-by-4, and Jagged Accumulate.

ASC ANDROMEDA Service Center.

BER Bit Error Rate.

BP Bundle Protocol.

BPSK Binary Phase Shift Keying.

C&S Coding & Synchronization.

CCSDS Consultative Committee for Space Data Systems.

CDM Code Division Multiplexing.

CDMA Code Division Multiple Access.

CFDP CCSDS File Delivery Protocol.

COP-P Communications Operation Procedure - P.

DART Double Asteroid Redirection Test.

DFE Direct-from-Earth.

DL Data Link.

DTE Direct-to-Earth.

DTN Delay/Disruption Tolerant Network.

DVB-S2 Digital Video Broadcasting - Satellite 2° generation.

DWE Direct-with-Earth.

ECSS European Cooperation for Space Standardization.

EID Endpoint ID.

ENCAP Encapsulation Packet Protocol.

EPP Encapsulation Packet Protocol.

ESA European Space Agency.

EVA Extra Vehicular Activity.

FDM Frequency Division Multiplexing.

FIR Finite Impulse Response.

FPGA Field-Programmable Gate Array.

GMSK Gaussian Minimum Shift Keying.

GS Ground Station.

ICI Interchannel Interference.

ID Identifier.

IDFT Inverse Discrete Fourier Transform.

IFFT Inverse Fast Fourier Transform.

IOAG Interagency Operations Advisory Group.

IP Internet Protocol.

IPoC IP over CCSDS.

ISO International Organization for Standardization.

ITU International Telecommunication Union.

LA Lunar Asset.

LDPC Low Density Parity Codes.

LICIA Light Italian CubeSat for Imaging of Asteroids.

LTE Long Term Evolution.

LTP Licklieder Transfer Protocol.

MAP Multiplexer Access Point.

MAP ID MAP Identifier.

MAPA MAP Access Service.

MAPP MAP Packet Service.

MATLAB MATrix LABoratory.

MC Master Channel.

MCC Mission Control Center.

MCID Master Channel Identifier.

MCN Mars Comm/Nav.

MSK Minimum Shift Keying.

NASA National Aeronautics and Space Administration.

OQPSK Orthogonal Quadrature Phase Shift Keying.

OSI Open System Interconnections.

PCID Physical Channel Identifier.

PDU Protocol Data Unit.

PFS1a Proximity Forward S-Band Data Only.

PFS1d Proximity Forward S-Band High Rate Data Only.

PL Physical Layer.

PLTU Proximity Link Transmission Unit.

Prox-1 Proximity-1.

PVN Packet Version Number.

QoS Quality of Service.

QPSK Quadrature Phase Shift Keying.

RF Radio Frequency.

SCID Spacecraft Identifier.

SDR Software Defined Radio.

SFCG Space Frequency Coordination Group.

SLS Space Launch System.

SNR Signal-to-Noise Ratio.

SPP Space Packet Protocol.

TC Telecommand.

TCP Transmission Control Protocol.

TDM Time Division Multiplexing.

TF Transfer Frame.

TFVN Transfer Frame Version Number.

TM Telemetry.

TMTC Telemetries and Telecommands.

UDP User Datagram Protocol.

UHF Ultra High Frequency.

URI Uniform Resource Identifier.

USLP Unified Space Data Link Protocol.

USRP Universal Software Radio Peripheral.

VC Virtual Channel.

VCID Virtual Channel Identifier.

VSA Vector Signal Analysis.

Wi-Fi Wireless Fidelity.

WLAN Wireless Local Area Network.

Non arrenderti.
Rischieresti di farlo
un'ora prima del miracolo

[Proverbio arabo]

Chapter 1

Introduction

1.1 Background and Motivation

Ever since the end of *Apollo Project* in 1970s, humans have the idea of returning to the Moon. Among the many reasons that led to the project cancellation, the main ones were the extremely high costs and the security concerns. The rapid technological advancement experienced especially in the last few decades has made possible the development of new, safer, and advanced materials. Also, thanks to researches in the aerospace field, a significant cost reduction has been observed. Specifically, the advent of *Falcon 9* reusable rocket from *SpaceX* represents a turning point for journeys to outer space. Furthermore, the increasing hunger for knowledge concerning the universe brought to the development of more and more scientific probes, like the well known *Perseverence* and *James Webb Space Telescope* (lauched by NASA in 2020 and 2021 respectively).
Thanks to all what mentioned, there are now plenty of planned missions to the Moon: a new era of space exploration has just begun. In fact, Earth's natural satellite has become again of particular interest for scientific discovery, economic benefits, and inspiration for new generations. One of the leading projects in this direction is represented by the *Artemis Project*, which aims to land the first woman and the first person of color on the Moon, to explore more of the Lunar surface than ever before. Another goal for *Artemis* missions is to establish the first long-term human presence on the Moon, with the objective to exploit it as a stepping stone for deep

space exploration.

In this context of growing scientific and commercial interest in the Moon, the Italian company *Argotec* designed ANDROMEDA: a telecommunication infrastructure aimed at providing a data relay service to users anywhere on its surface, granting global access to Lunar resources and extensive data exchange with Earth. The large number of planned missions for the coming years requires ANDROMEDA to be able to serve more than one asset simultaneously. This thesis work focuses indeed on the development of a multi-user architecture within the ANDROMEDA framework.
Among the many issues a multi-user architecture deployed in space has to face, the most challenging one is represented by the lack of supporting protocols and recommendation. Indeed, up to the very recent years, there was no need to communicate with more than a single spacecraft at a time. Fortunately, the latest released standards included the possibility of more than single point-to-point link, but further improvements are necessary.
Furthermore, this thesis work will also face another innovative aspect since it will deal with a Frequency Division Multiplexing (FDM) scheme. This choice was made because of the extra coordination burden needed to both Earth and space assets to correctly synchronize in case of a Time Division Multiplexing (TDM) multi-user architecture.

1.2 Argotec

Argotec is a fast growing Italian aerospace company, founded in Turin by David Avino in 2008. At the present day, the company pillars are the training and well-being of astronauts together with the development of small-sized satellites for deep space missions. *Argotec* philosophy follows the *all-in-house* principle: all the phases of the production process from design to integration, testing and assembly, take place inside internal facilities (laboratories and cleanroom). Following this principle the company produced two microsatellites that were selected to be onboard NASA's latest missions: *LICIACube* and *ArgoMoon*.
LICIACube is the only CubeSat to be part of the Double Asteroid Redirection Test (DART) mission for the documentation of the change in the

trajectory of two binary asteroids after a probe's impact. Specifically, it was built to communicate directly with Earth, sending back images of the plume ejecta of DART's impact as well as do asteroidal study during its flyby of the Didymos system, few minutes after DART's impact. *LICIACube* was successfully launched on 24 November 2021 and correctly deployed on 11 September 2022, 15 days before the probe impact. On the night of September 26-27, DART successfully completed its mission by crashing on Dimorphos. A few minutes later LICIACube also successfully carried out its mission by taking more than 600 photos of the event.
ArgoMoon, on the other hand, is scheduled to be launched in November 2022 onboard the new American Space Launch System (SLS) for the *Artemis 1* mission as the only European secondary payload. The satellite's objective is to take detailed images of the Interim Cryogenic Propulsion Stage after Orion[1] separation, an operation that aims to demonstrate the ability of a CubeSat to conduct precise proximity maneuvers in deep space. *ArgoMoon* will complete its operations using proprietary software for autonomous navigation.

With the growing number of planned and proposed scientific and commercial missions towards the Moon, a new era of space exploration is seeing the light, carried on by a vision of sustainable and long-term inhabitation. To fulfill assets communication needs, a telecommunication infrastructure has been designed by *Argotec*: ANDROMEDA. Along with this project, the company is currently working on *Mars Comm/Nav* (MCN) project which aims to an early deployment of a constellation of small satellites with communication and navigation capabilities at Mars. The main differences between the two are that ANDROMEDA performs orbit determination and provides ranging to users via two-way ranging through Earth, while MCN performs autonomous orbit determination and will provide to users one-way ranging. Both projects are part of a larger number of end-to-end services for deep space exploration assets on which the company is working on, given the global increasing interest in the subject.
In chapter 2 the ANDROMEDA project will be better discussed since this

[1]The Orion spacecraft is the primary payload of Artemis 1.

thesis work falls within it.

1.3 Thesis Outline

The current section describes the organization of the thesis work and gives a brief description of the content of each chapter.

Chapter 2 gives a more in-depth overview about the ANDROMEDA project, together with some technical specifications and some insights about its concept of operations. Furthermore, it reports some additional requirements for the multi-user architecture needs.

Chapter 3 describes all CCSDS protocols that have been considered for eventual selection to be part of the system protocol stack. Then, it reports the protocol stack trade-off analysis and its outcomes. Some useful use cases are also described.

Chapter 4 analyses the Data Link Layer of the multi-user architecture, reporting the chosen multiplexing processes to be applied to it. Later in the chapter the Coding & Synchronization Sublayer is considered, with a focus on coding techniques to be utilized by the architecture.

Chapter 5 presents a detailed analysis of standards and recommendations regarding the Physical Layer. Next, first the modulation schemes to be implemented are described, then the strategy adopted to achieve a multi-user implementation with all the related technical specifications.

Chapter 6 deals with the architecture validation and testing, focusing on the Physical Layer. Specifically, to test the multi-user architecture, a test bench has been set up to simulate a realistic simplified scenario (neglecting the propagation conditions which are not the focus of this work). The test bench organization is described, and the obtained results are analyzed in depth.

Chapter 7 closes the thesis by discussing the main conclusions and possible future developments of the work.

Chapter 2

End-to-End System

2.1 ANDROMEDA Architecture

The ANDROMEDA project [1, 2] aims to provide a Lunar communication and navigation end-to-end service based on a constellation of microsatellites. Exploiting microsatellites in a relatively high number can maximize coverage performances and system redundancy, with contained costs when compared to larger platforms. ANDROMEDA is designed to provide end-to-end communication service that is highly compatible and flexible with respect to the progressive growth of Lunar Assets (LAs) and their respective data needs over time. Also, thanks to the long-term projected presence of ANDROMEDA as an Earth-Moon network node, future Lunar missions will be able to design platforms with leaner communication subsystems, thus leaving room for bigger payloads or redundant critical components.
ANDROMEDA system is compliant to frequency plans for Lunar region assessed by both the Space Frequency Coordination Group SFCG) Recommendation [3] and the European Cooperation for Space Standardization (ECSS) [4]. Together with these frequency assignment recommendations, it must also be mentioned another document to be used as a reference: the report released early this year by Interagency Operations Advisory Group (IOAG) concerning the future Lunar communication architecture [5]. In that research work, all the known missions launched and planned to be launched towards the Moon during the 2018-2030 timeframe were analyzed. The report accurately summarizes all frequencies, modulations, and

coding schemes which have been used and are planned to be used for such missions, also considering the latest released CCSDS standards (such as USLP and optical links).
On top of all these baseline recommendations, NASA built its plan to bring internet-like capabilities to the Moon: LunaNet Interoperability Specification [6]. LunaNet is envisioned as a set of cooperating networks providing communications, navigation and other services for users on and around the Moon. The LunaNet concept is based on a framework of mutually agreed-upon standards, protocols, and interface requirements that enable interoperability and therefore specifies working frequencies, suggested modulations and coding for each service type. Despite still being under development, LunaNet is already a landmark for any company or agency that is planning Lunar missions for the coming years. As such, ANDROMEDA is a communication service compliant to it.

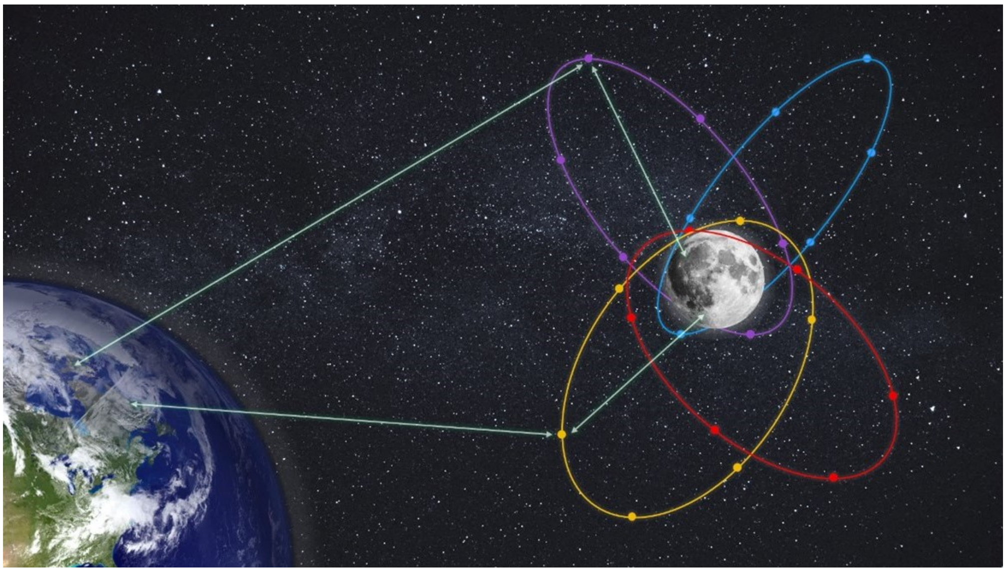

Figure 2.1: The ANDROMEDA constellation

The entire ANDROMEDA system architecture is divided into four different segments (as depicted in Figure 2.2):

- Space Segment
- Launch Segment

- Ground Segment
- Lunar User Segment

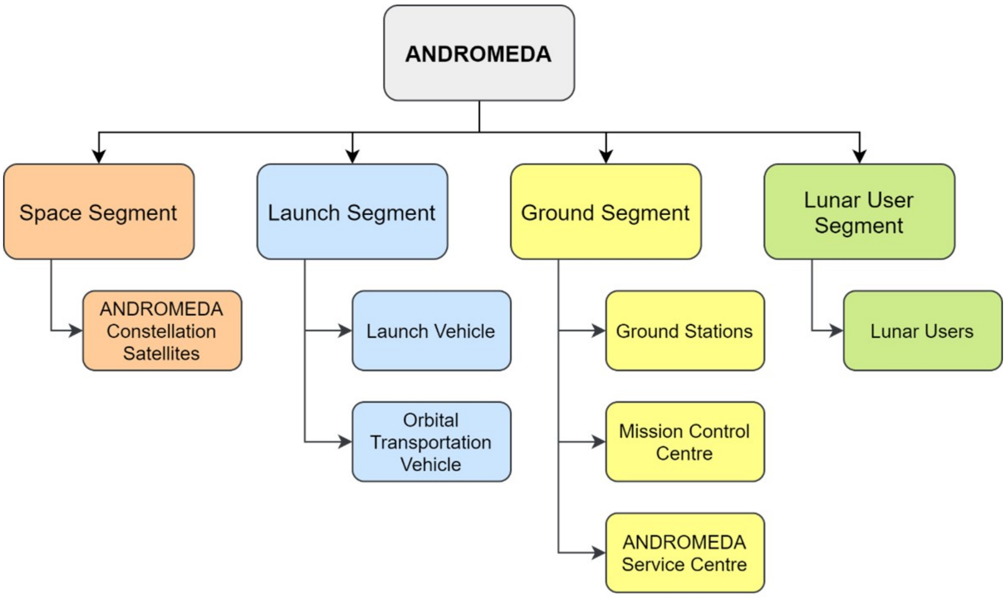

Figure 2.2: Baseline Architecture - Segment tree

At the core of the ANDROMEDA space segment there are the constellation satellites, orbiting the Moon and in charge of the communication and navigation services provisioning. Data relay occurs via each satellite individually, thus without inter-satellite links, so that each satellite needs to establish direct links both with Lunar Assets (LAs) and Earth's Ground Stations (GSs). The nominal ANDROMEDA architecture is defined by 24 satellites orbiting the Moon along 4 elliptical orbital planes which are depicted in Figure 2.1. This orbital configuration allows to increase global performance in terms of coverage and service continuity. However, the architecture needs to establish multiple Earth-Moon links at a time to increase the system performance in terms of data volume.
The launch segment is instead composed by the launch vehicle and the orbital transportation vehicle.
As for the Earth Ground Segment, three elements are included: Ground

Stations, Mission Control Center (MCC), and ANDROMEDA Service Center (ASC). GSs connect the space segment with Earth to allow data exchange, while the MCC and the ASC are responsible for constellation management and user data distribution.
Finally, the user segment is essentially composed by Lunar users, either on the Lunar surface or orbiting the Moon that can benefit from the ANDROMEDA services.

2.2 Space Segment Specifications

The main activity to be performed by the constellation is the ANDROMEDA services provisioning, hence satellites will be able to cover the entire Lunar surface, with a priority on high-latitude and polar regions, where a 24/7 service will be accessible by user assets. Indeed, Figure 2.3 shows the main Lunar regions of interest that will be explored by planned and future missions.

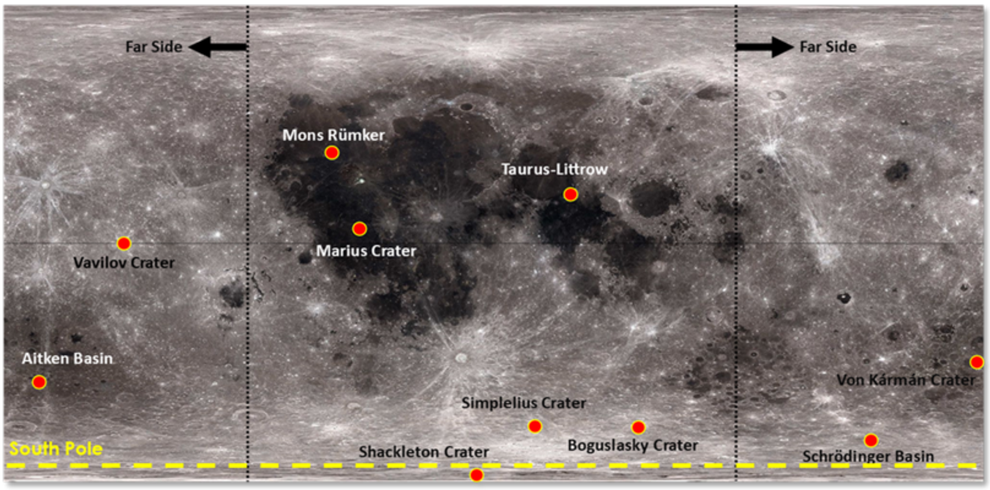

Figure 2.3: Lunar regions of interest

Overall, the exchanged data with Earth can include:

- User data (e.g., video, voice, images, and scientific data)
- User Telemetries and Telecommands (TMTC)

As a communication baseline, ANDROMEDA has been designed to provide the following types of service:

- Moon-to-Earth Communication
- Moon-to-Moon Communication

Both real-time and store & forward communication approaches will be available to users. In the real-time service, a double link is established to connect Lunar user, ANDROMEDA orbiter, and Earth station at the same time. In the store & forward service, user data and TMTC are transmitted to the constellation satellites where they are stored and sent later to the Ground Network on Earth. For the Moon – Earth communication, communication windows can be either scheduled from Earth or negotiated autonomously between the Lunar user and the ANDROMEDA constellation. Figure 2.4 shows how the store & forward approach is carried out

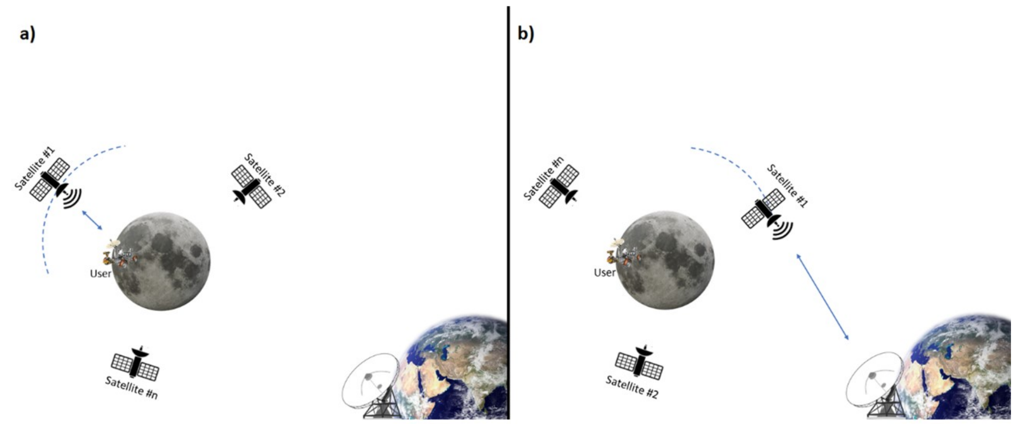

Figure 2.4: Store & forward communication scenario (Moon-to-Earth)

to allow Lunar users to communicate with Earth. If data exchange is performed with a real-time approach, steps a) and b) occur simultaneously and the Lunar user is provided with an instant communication window with Earth. Obviously, real-time communication requires that the satellite involved is simultaneously covered by a GS and has the user in visibility.
For the Moon-to-Moon communication, data generated by a Lunar user is transferred by the constellation to another user on the surface or orbiting

the Moon. This type of service guarantees data exchange from and to LAs creating a network that is handled autonomously by ANDROMEDA, without additional burden on Earth's Ground Stations.
One of the key innovation aspects about ANDROMEDA is the support to real-time communication. Given the technology advancements of the last few decades, it is feasible to imagine that there will be assets on the Moon requiring fast as well as with high capacity and high data rates links. Recalling that one of the goals for *Artemis* mission is to bring back humankind on the Lunar surface, it is expected that they will require the possibility to directly communicate with Earth, for example by means of video-calls. Also, it is forecasted that rovers will have the possibility to be remote-controlled by operators on Earth and that landers will require real-time data streams too. In this scenario, ANDROMEDA is designed to support all these needs, allowing for video, audio, and data to be exchanged in (almost) real-time.
As stated previously, the ANDROMEDA orbiting assets cannot establish cross-links and all of them will have the capabilities to communicate directly with Earth, without using any satellite aggregator for the Earth - ANDROMEDA link. In the Moon-ANDROMEDA link, instead, all satellites will have the capabilities to communicate with multiple Lunar users at a time to have a multi-user system able to serve users located in different Lunar regions.

A company market analysis revealed that the system shall support a maximum of 100 Mbps aggregated data rate (real-time or store & forward) for the Direct-to-Earth (DTE) link (from Lunar region to Earth) and 32 Mbps for the Direct-from-Earth (DFE) link (from Earth to Lunar region); the latter specification is compliant to [7]. Specifically, this CCSDS recommendation envisions that in order to support human presence at the Moon with applications that may include voice, video, and Internet traffic it will be necessary to support data rates of at least 20 Mbps.
With references to [5] and [6] DWE links, assuming to use both efficient coding schemes (e.g. LDPC $1/2$) and efficient modulation schemes (e.g. OQPSK, roll-off $=$ 0.5), it must be considered that the transmission occupied bandwidth is equal to 176 MHz (for OQPSK, roll-off $=$ 0.5 the

occupied bandwidth is equal to 0.88 times the symbol rate [8]). According to SFCG Recommendations [3], the available bandwidth in the return link for each frequency band is:

- S-Band: $90\,$MHz
- X-Band: $50\,$MHz
- K-Band: $1.5\,$GHz
- Ka-Band: $1\,$GHz

Eventually, K-band results to be the only frequency band suitable for the DWE. Hence, ANDROMEDA will use the K-band for the Direct-With-Earth link.
For what concerns the proximity[1] link, whose Physical Layer is the main focus of this work, instead, the previously mentioned market analysis and the ESA Phase A study of lunar communications and navigation mission report - Annex B [10] have been taken as input to categorize the different next Lunar missions in terms of type and frequency bands. Table 2.1 summarizes analyses outcomes.
Considering S-Band and K-Band as a baseline for the ANDROMEDA - Lunar user link, the system can be compliant with the entire set of Lunar users. Moreover, exploiting the selected frequency bands it is possible to meet all users' data rates needs for both the forward and the return links. Also, referring again to the market analysis mentioned earlier, a maximum of 3 Lunar users can be served at the same time by each satellite (distributed between S-Band and K-Band proximity links), since missions distribution along time has such few overlaps among assets needing service.

[1] With this term is denoted a space communication link which ranges between $\sim 1\,$m and approximately $10^5\,$km, though greater distances could be accommodated [9]

Table 2.1: Lunar user frequency bands analysis

User Type	Frequency Bands
Robotic Vehicles (landing/ascent)	S, K
Manned Vehicles (landing/ascent)	S, K
Autonomous Rovers	UHF, S
Tele-Operated Rovers	K
Lunar Orbiters	S, K
Rendez-vous Missions	S, K

2.3 Multiuser Architecture Requirements

The main features of ANDROMEDA baseline architecture described in the previous section are summarized below:

- 24 satellites are distributed along 4 elliptical orbits around the Moon
- satellites cannot establish cross-links
- satellites can provide both real-time and store & forward services
- satellites working frequencies: S-Band and K-Band (proximity links); K-Band (DWE links)
- ANDROMEDA is designed to be a multi-user system

[redacted].

Table 2.2: Multiuser architecture requirements and rationale.

[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
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Chapter 3

Protocol Stack Analysis

3.1 Protocol Stack Definition

Terrestrial proposed, well-known and utilized internetworking protocols do not suit well the space environment due to their different characteristics. The internet infrastructure on Earth relies on stable fiber optic-based network with an almost fixed topology characterized by low error rates, extremely high capacities and small latencies (few hundreds milliseconds). On the contrary, space communication is completely different. It is characterized by high latencies, higher error probabilities (with respect to terrestrial ones) and lower available link capacities. Moreover, there is the possibility of not being able to transmit due to lack of visibility between GSs and spececrafts. Given the two very different set of characteristics, most of the terrestrial communication standards do not suit well for space. Therefore, CCSDS released several protocols (from application to physical layer) and recommendations to be used for space missions to promote interoperability and cross support between agencies, multi-agency spaceflight collaboration and overall cost reduction.
The paradigm that the vast majority of past space missions followed (and most of the upcoming ones will) is that of a point-to-point communication between a spacecraft and the ground segment on Earth. Consequently, all the proposed communication standards were built to work according to such a paradigm. Nevertheless, the Proximity-1 standard [9] includes possibility of a multi-channel and multi-connection extension communication

among users. Furthermore, the ISO/OSI strict scheme used for terrestrial communication standard protocols definition does not equally apply to the proposed protocols for space utilization. Indeed, among the latter ones, it is possible to find some that have Application Layer functionalities (Layer 7 of the ISO/OSI protocol stack) as well as functionalities that sit between the Network and the Data Link Layers (Layers 3 and 2 of the ISO/OSI protocol stack respectively).
Section 3.1.1 are summarizes, divided according to their ISO/OSI reference layer, all the CCSDS protocols analyzed with a focus on their functionalities that may result to be useful for a multi-user architecture implementation. It must be noticed that in addition to all the CCSDS protocols, in section 3.1.1 some of the terrestrial standards that may be utilized in space environment are mentioned. For example, by exploiting Encapsulation Packet Protocol (EPP or ENCAP) functionalities [11] it is possible to adopt the Internet Protocol (IP) suite also for space links [12]. A visual, clarifying representation of all these protocols is depicted in Figure 3.1 according to the ISO/OSI conceptual model. Moreover, both the Interagency Operations Advisory Group (IOAG) Lunar Communication Architecture Recommendation [5] and LunaNet Interoperability Specification [6] expect that WLANs on the Lunar surface will be using 802.11x and possibly 3GPP standards (like LTE). Consequently, there are many different possibilities for protocol stack implementation. The ones that were considered for the trade-off analysis are listed in Table 3.1.

3.1.1 Selected Protocols General Description[1]

In the following, all protocols that have been selected as possible candidates to be part of the protocol stack are reported and analyzed, divided by Layer. Their visual representation with reference to the standard ISO/OSI model is represented in Figure 3.1.

[1]For more in depth details refer to [13]

Physical Layer

CCSDS has an omnibus[2] standard for the Physical Layer (PL) called Radio Frequency and Modulation Systems [14] to be used for space links between spacecraft and ground stations. This protocol is adopted by Advanced Orbiting System (AOS) [15] standard for its PL. AOS is deepened in next paragraph.
A second CCSDS protocol, namely the Proximity-1 (Prox-1) Space Link Protocol [9], contains itself recommendations for the PL of proximity space links.
For this study both options will be considered, since satellites must communicate with both Earth (hence using AOS) and the Lunar region (exploiting Prox-1).

Data Link Layer

CCSDS formally subdivides the Data Link (DL) Layer in a Data Link Protocol Sublayer and a Coding & Synchronization (C&S) Sublayer, as clearly highlighted in Figure 3.1. However, the figure also shows that not all proposed protocols provide recommendations for both Sublayers as better specified later in this paragraph. Obviously, C&S Sublayer implementation guidelines strongly depend on the choices concerning the DL Protocol Sublayer.
Several protocols have been developed through the years by CCSDS for the Data Link Layer. Among them, the following ones were selected:

- AOS Space Data Link Protocol [15]
- Proximity-1 [16]
- Unified Space Data Link Protocol (USLP) [17]

All these protocols provide the capability to transfer various types of data on space links, but their principal function is to transfer data units known as packets. Each packet format transferred by the Space DL Protocols must

[2] A volume containing several recommendations previously published separately

have a Packet Version Number (PVN) recognized by CCSDS. Nevertheless, CCSDS has another mechanism to transfer protocol data units (PDUs) of CCSDS and non-CCSDS protocols by means of EPP, but this will be discussed in the next paragraph. The PDUs used by all these protocols are called Transfer Frames (TF).
A key feature of these Space Data Link Protocols is the concept of "Virtual Channels". The Virtual Channel (VC) facility allows one Physical Channel to be shared among multiple higher-layer data streams, each of which may have different service requirements. A single Physical Channel may therefore be divided into several separate logical data channels, each known precisely as a Virtual Channel. Every Transfer Frame transferred over a Physical Channel belongs to one of the Virtual Channels of the Physical Channel.
A key functionality to be considered for the DL Layer is the addressing capability, since it is of extremely importance for a multi-user architecture. The selected Data Link Protocols have the following identifiers:

- Transfer Frame Version Number (TFVN) – All
- Spacecraft Identifier (SCID) – All
- Virtual Channel Identifier (VCID) – AOS, USLP
- Physical Channel Identifier (PCID) – Prox-1
- Multiplexer Access Point Identifier (MAP ID) – USLP
- Port Indentifier (Port ID) – Prox-1

The TFVN is used to distinguish among different Transfer Frames, i.e. identifies which protocol created it. However, different Transfer Frames must not be multiplexed on a Physical Channel.
The concatenation of a TFVN and a SCID is known as a Master Channel Identifier (MCID), which is used for identifying a spacecraft associated with a space link.
All Transfer Frames with the same MCID on a Physical Channel constitute a Master Channel (MC). A Master Channel consists of one or more Virtual

Channels, each of which is identified with a VCID. In most cases, a Physical Channel carries only Transfer Frames of a single MCID, and the Master Channel will be identical with the Physical Channel. However, a Physical Channel may carry Transfer Frames with multiple MCIDs (with the same TFVN). In such a case, the Physical Channel consists of multiple Master Channels. A Physical Channel is identified with a Physical Channel Name, which is set by management and not included in the header of Transfer Frames.
In the following, each previously listed protocol is more in depth analyzed, reporting its main peculiarities.

AOS:
AOS uses fixed-length TF to facilitate robust synchronization procedures over a noisy link. It may be used on a return link alone, or on both forward and return links if there is a need for two-way higher speed communications (e.g., audio and video) between a spacecraft and the ground.
However, it does not implement any retransmission feature for missing or corrupted frames, so retransmission must be done by a higher-layer protocol.
The AOS protocol should be used together with the TM Synchronization and Channel Coding Recommended Standard [18] at the C&S Sublayer and on top of the Recommended Standard for Radio Frequency and Modulation Systems [14] at the Physical Layer.

Proximity-1:
The Proximity-1 is to be used over proximity space links, where proximity space links are defined to be short range, bi-directional, fixed or mobile radio links, generally used to communicate among fixed probes, landers, rovers, orbiting constellations, and orbiting relays.
The Transfer Frame used by Proximity-1 are of variable-length to facilitate reception of short messages with a short delay. Furthermore, it has a function for retransmitting lost or corrupted data to ensure delivery of data in sequence without gaps or duplication over a space link called Communications Operation Procedure-P (COP-P) (this function does not necessarily guarantee end-to-end complete delivery).

The Proximity-1 uses a triad of multiplexing capabilities, which is incorporated for specific functionalities within the link. The SCID identifies the source or destination of Transfer Frames transported in the link connection based upon the Source-or-Destination Identifier filed in TF header. The PCID provides up to two independently multiplexed channels. The Port ID provides the means to route user data internally (at the transceiver's output interface) to specific logical ports, such as applications or transport processes, or to physical ports, such as onboard buses or physical connections (including hardware command decoders).
The Proximity-1 Space Link Protocol - Data Link Layer [16] should be used together with the Proximity-1 Space Link Protocol - Data Coding and Synchronization Layer [19] and on top of the Proximity-1 Space Link Protocol - Physical Layer [20].

USLP:
The USLP goal is to replace all the other Space Data Link Protocols in the coming years because of its extreme flexibility, as it was designed to incorporate all the features of its predecessors. For example, USLP provides to implementers both fixed-length and variable-length Transfer Frames.
Also USLP implements the COP-P procedure (as Prox-1 does) for recovery of lost or corrupted data. Another common peculiarity between USLP and Prox-1 is the SCID that even in this case defines Transfer Frames source or destination based upon the Source-or-Destination Identifier.
Additionally to identifiers of both AOS and Prox-1, the USLP uses an optional one, called the Multiplexer Access Point Identifier (MAP ID), that is used to create multiple streams of data within a Virtual Channel. All the Transfer Frames on a VC with the same MAP ID constitute a MAP Channel. If the MAP ID is used, a Virtual Channel consists of one or multiple MAP Channels.
At the Coding & Synchronization Sublayer, the USLP should be used together with AOS or Proximity-1 C&S Sublayers, as well as on top of AOS or Proximity-1 at the Physical Layer.

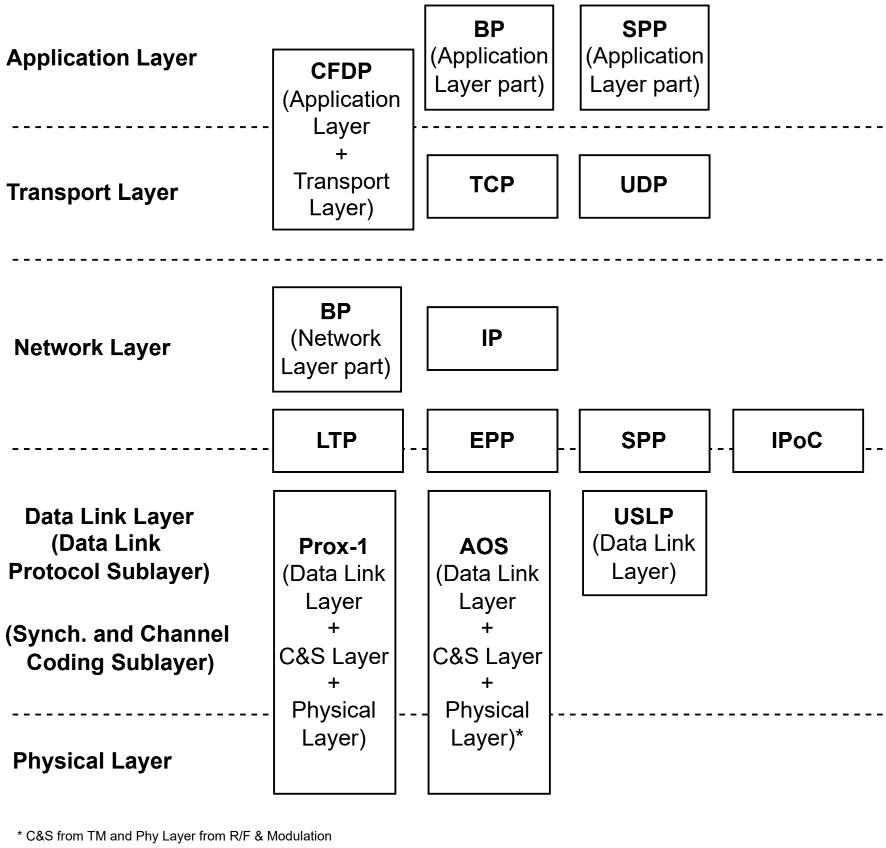


Figure 3.1: Protocols selected for trade-off analysis visual reference model

Between Data Link and Network Layers

CCSDS has different services for interfacing at the Network Layer: Encapsulation Packet Protocol (EPP or ENCAP) [11], Space Packet Protocol (SPP) [21], Licklider Transfer Protocol LTP [22] and IP over CCSDS [12]. Within these services, there are 3 different types of packets: Space Packets defined in the SPP, Encapsulation Packets defined in the EPP and IP datagrams.
It should be noticed that IPoC can exclusively be utilized on top of Encapsulation Packets.
The Space Packet Protocol was developed to transfer data either from a source on a spacecraft to one or multiple destinations on the ground or on (an)other spacecraft, or from a source on the ground to one or multiple

destinations on one or multiple spacecraft. When protocol data units of this protocol traverse the data system of a space mission (i.e., onboard networks, onboard data handling system, ground stations, control centers), the application identifier that is part of each packet is used for determining the path that packet will take (all decisions about how packets are to be handled and forwarded, based on this ID, are set by management agreement).
By using the Encapsulation Packet Protocol, other CCSDS-recognized Network Protocols such as Delay Tolerant Networking (DTN) [23] and IP can be used over space links. SPP, EPP, and IP do not provide any QoS mechanisms for reliable delivery, in-order delivery, or duplicate suppression.
The Licklider Transmission Protocol (LTP) provides optionally reliable communications over a single data link hop. CCSDS has identified requirements for a protocol, i.e., LTP, to sit between an internetworking protocol such as the Bundle Protocol and the various CCSDS data links. The requirements identified for such a layer-N protocol are reliable delivery of layer-(N+1) PDUs and the ability to aggregate multiple layer-(N+1) protocol data units into a single layer-N PDU for the purposes of reliable delivery across the link. Reliable data delivery is accomplished by the red-part delivery service of the LTP protocol. Aggregation of multiple layer-(N+1) service data units into a single layer-N PDU (LTP block) is achieved by the implementation of the standardized "Service Data Aggregation" client operation. The rationale for aggregating multiple layer-(N+1) PDUs into a single layer-N PDU for the purposes of reliable delivery is that it may allow the system to reduce the acknowledgement-channel bandwidth in the case that the layer-(N+1) (and higher) protocols transmit many small PDUs, each of which might otherwise require independent acknowledgement.

Network Layer

The two identified protocols that can be used are the Bundle and the Internet Protocols.
The Internet Protocol (IP) is responsible for addressing host interfaces,

encapsulating data into datagrams (including fragmentation and reassembly) and routing datagrams from a source host interface to a destination host interface across one or more IP networks.
The Bundle Protocol (BP) [24] provides end-to-end network services, operating above the data transport services provided by links or networks accessed via convengence layer adapters (which may include the IP suite ones as well), and forming a store-and-forward network. Key capabilities of the Bundle Protocol include:

- ability to cope with intermittent connectivity
- ability to take advantage of scheduled, predicted, and opportunistic connectivity (in addition to “always up” connectivity)
- custody transfer
- hop-by-hop security (authentication of transmitting entity)
- end-to-end security (confidentiality, integrity) for data
- late binding of names to addresses

BP space implementations shall support the URIs "ipn" naming scheme to reduce transmission overhead (as stated in [24]). The "ipn" consists in the following scheme: "ipn:node_number.service_number"; endpoint IDs formed in the "ipn" scheme can be abbreviated to pairs of unsigned binary integers. All BP endpoints identified by ipn-scheme endpoint IDs are singleton (i.e., uniquely identified) endpoints.

Transport Layer

CCSDS File Delivery Protocol (CFDP) [25] provides functionalities of the Application Layer (i.e., functions for file management), but it also provides functions of the Transport Layer like multi-hop file copying with limited store-and-forward capabilities (and without end-to-end guarantees).
Transport protocols used in the Internet (such as TCP and UDP) can also be used on top of the Encapsulation Packet, or IP over CCSDS space links.

Table 3.1: Possible protocol stack implementations considered for the trade-off analysis

APPLICATION Layer-7	**TRANSPORT Layer-4**	**NETWORK Layer-3**	**Between Layer 3 and 2**	**DATA LINK Layer-2**	**PHYSICAL Layer-1**
Any	-	BP	LTP+ENCAP	USLP	Prox-1/AOS
Any+BP	TCP	IP	IPoC+ENCAP	USLP	Prox-1/AOS
Any+BP	UCP	IP	IPoC+ENCAP	USLP	Prox-1/AOS
Any	TCP	IP+BP	LTP+ENCAP	USLP	Prox-1/AOS
Any	UDP	IP	IPoC+ENCAP	USLP	Prox-1/AOS
Any	-	BP	ENCAP	USLP	Prox-1/AOS
Any	CFDP	-	ENCAP	USLP	Prox-1/AOS
Any	TCP	IP	IPoC+ENCAP	USLP	Prox-1/AOS
Any	UDP	IP	IPoC+ENCAP	USLP	Prox-1/AOS
Any	-	-	LTP+ENCAP	USLP	Prox-1/AOS
Any	-	-	-	USLP	Prox-1/AOS

3.1.2 Metrics Definitions

[redacted]

- [redacted]
  - [redacted]
  - [redacted]
  - [redacted]
  - [redacted]
  - [redacted]
  - [redacted]

  [redacted]

- [redacted]

- [redacted]

Table 3.2: [redacted] - trade-off criterion

	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	≤ [redacted]
		[redacted]	[redacted]
		[redacted]	[redacted]
		[redacted]	[redacted]
		[redacted]	≥ [redacted]

Table 3.3: [redacted] - trade-off criterion

	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
		[redacted]	[redacted]
		[redacted]	[redacted]
		[redacted]	[redacted]
		[redacted]	[redacted]

Table 3.4: [redacted] - trade-off criterion

	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
		[redacted]	[redacted]
		[redacted]	[redacted]
		[redacted]	[redacted]
		[redacted]	[redacted]

- [redacted]

Table 3.5: [redacted] - trade-off criterion

	[redacted]	[redacted]	[redacted]
		[redacted]	[redacted] ≤ [redacted]
		[redacted]	[redacted] ≤ [redacted]
[redacted]	[redacted]	[redacted]	[redacted] ≤ [redacted]
		[redacted]	[redacted] ≤ [redacted]
		[redacted]	[redacted]

- [redacted]

Table 3.6: [redacted] - trade-off criterion

	[redacted]	[redacted]	[redacted]
		[redacted]	≥ [redacted]
		[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
		[redacted]	[redacted]
		[redacted]	≤ [redacted]

3.1.3 Trade-off Analysis

[redacted]

[redacted]

[redacted]

Table 3.7: Protocol stack trade-off analysis results

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

3.2 Use Cases

[redacted]

- [redacted]
- [redacted]

3.2.1 Assumptions

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

3.2.2 One Earth based customer with 2 LAs

[redacted]

- [redacted]

- [redacted]

[redacted]

[redacted]

[redacted]

- [redacted]

- [redacted]

[redacted]

[redacted]

Figure 3.2: Use case 1 - One Earth based customer with 2 LAs, forward link representation

[redacted]

3.2.3 Two Earth based customers with one LA each

[redacted]

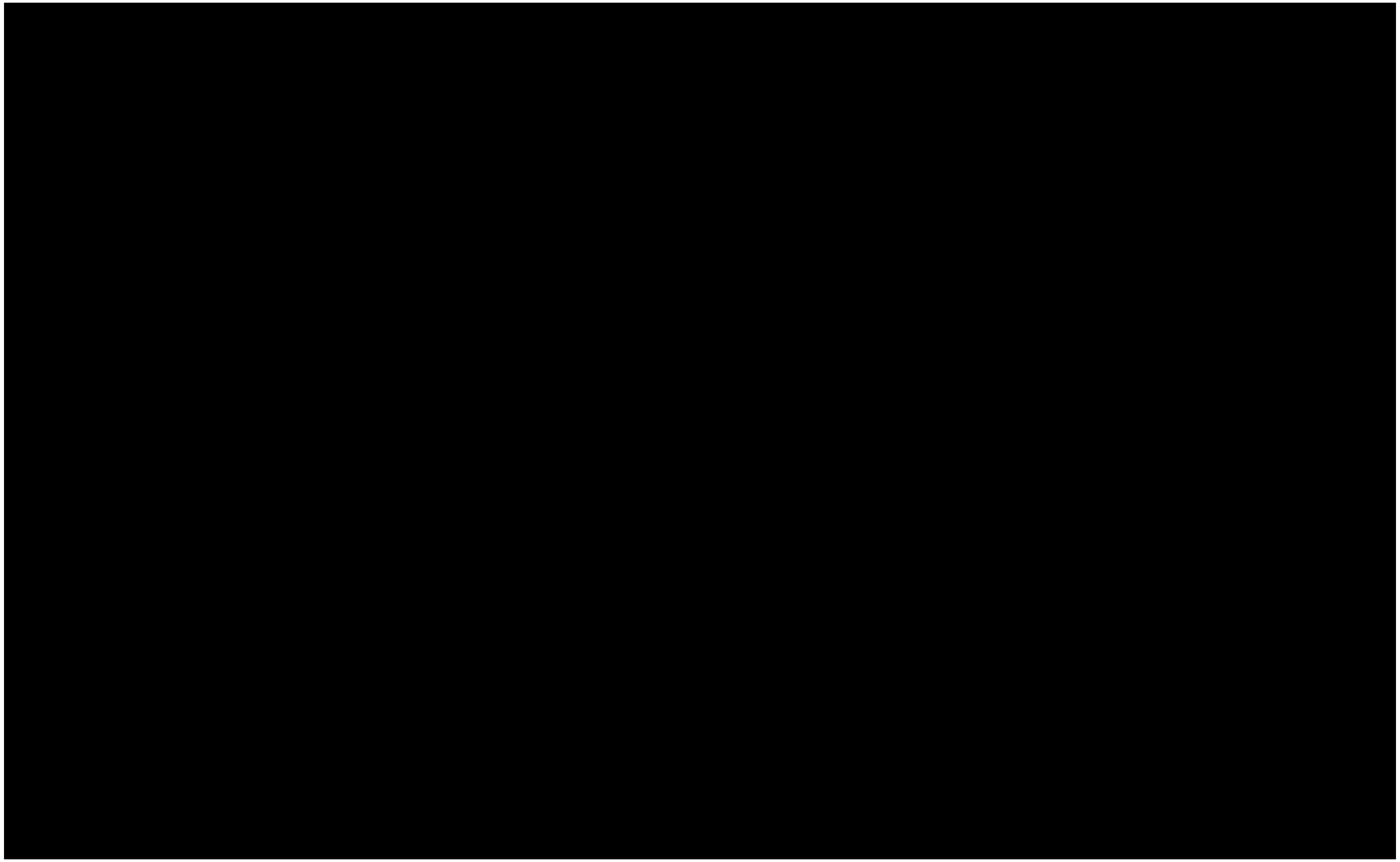


Figure 3.3: Use case 2 - two Earth based customers with one LA each, forward link representation

Chapter 4

Data Link Layer

Previous chapter discussed the entire protocol stack because of the need to identify the general structure for the architecture given its requirements. Nevertheless, the target was to identify a way to be able to uniquely distinguish users, satellites, and assets in general in order to be able to correctly perform multiplexing/demultiplexing of different data flows. Specifically, there has been a focus on the Data Link Layer and the possibilities that the identified protocol to be adopted, i.e. USLP, gives to implementers to identify, prioritize, and aggregate different data flows and users.

4.1 USLP Multiplexing Processes

One of the main purposes of the USLP Protocol is to unify (as its name suggests) in a single, universally used protocol all the functionalities of its predecessors and as such it gives high flexibility to implementers. However, this implies that every agency or company may design its own protocol version and this may lead to incompatibilities among spacecraft from different constructors. Recalling that ANDROMEDA's ultimate goal is to provide services to the highest possible number of spacecraft (and possibly to all), it is mandatory to assume that ANDROMEDA satellites will have to adapt to customers needs and consequently it is likely to assume that the protocol implementation must allow "on the fly" modifications.

The identifiers mentioned in section 3.1.1 should be considered for the definition of the multiplexing processes and among them the ones of interest are: MAP ID, VCID and SCID (if it is assumed that all entities involved in the communication implement USLP, as it is done in this study). The protocol do not specify any specific use of those identifiers (except for the SCID), hence it is left to implementers the choice of how to exploit them to best suit each mission.
Among all the implementation possibilities it was chosen to use MAP IDs to identify applications requesting Data Link Layer services, VCIDs to prioritize data flows (by protocol definition each MAP on a given VC share the same VC sequence counter and optional security process), and SCID to uniquely identify spacecraft (as by definition of SCID). Moreover, among each MAP there is the possibility to exploit the "*MAP multiplexing function*" to further prioritize among the three main services provided by the MAP, namely MAP Packet Service (MAPP), MAP Access Service (MAPA) and Octet Stream. Specifically:

- MAPP Service provides transfer of sequences of variable-length, delimited, octet aligned packets across a space link in a unidirectional and asynchronous manner; packets transferred by this service must have a PVN authorized by CCSDS

- MAPA Service provides transfer of a sequence of privately formatted service data units of variable length

- Octect Stream Service provides transfer of a string of aligned octets, whose internal structure and boundaries are unknown to the service provider, across a space link; the service is unidirectional, asynchronous, and sequence-preserving

It must be noticed and highlighted that this is a custom implementation choice that must be eventually compatible with any customer implementation. A visual representation of the chosen multiplexing process is depicted in Figure 4.1.

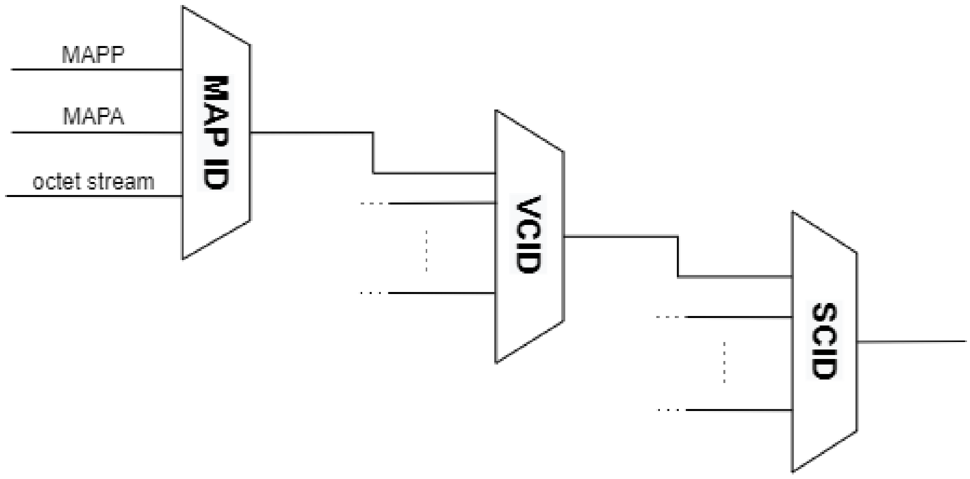


Figure 4.1: USLP multiplexing stage

4.2 Coding & Synchronization Sublayer

In section 3.1.1, specifically in the Data Link Layer subsection, it was mentioned and shown (Figure 3.1) that CCSDS identifies a Data Link Protocol Sublayer and a Coding & Synchronization Sublayer within the Data Link Layer itself. Also, not all proposed protocols cover the entire DL Layer. Indeed, the USLP only provides specifications for the implementation of the higher of the two, i.e., the Data Link Protocol Sublayer (whose multiplexing processes have been analyzed in previous section), while clearly stating that it should be used on top of either the Prox-1 or the AOS at both the C&S and Physical Layer. Therefore, since this work is mainly concerned with ANDROMEDA proximity forward[1] links, Proximity-1 was considered as the reference standard for the Coding & Synchronization Sublayer here discussed.

On the sender side, the C&S Sublayer of the Prox-1 generates the output coded symbols stream, called Proximity Link Transmission Unit (PLTU), to be delivered to the Physical Layer for modulation onto the radiated

[1]Space assets - Moon links

carrier. The PLTUs form a non-continuous serial stream, consisting of a sequence of variable-length PLTUs[2], which can have a delay between the end of one PLTU and the start of the next. While establishing a Prox-1 session for a link, synchronization is reacquired for each PLTU, and Idle data is provided for the acquisition process. When no PLTU is available, Idle data is transmitted to maintain synchronization.
According to the Prox-1 protocol specifications, the eligible coding schemes to be adopted are the following:

- no coding
- CCSDS Convolutional (7,1/2) Code
- CCSDS Low Density Parity Codes (LDPC) 1/2 Code

The Convolutional and LDPC codes are optional though their utilization is strongly suggested given the high coding gain they can achieve in terms of Bit Error Rate (BER) with respect to an uncoded communication as shown in Figure 4.2. Both coding schemes are briefly described below, taking [26] as a reference.
In addition to those mentioned above, the Prox-1 includes an option to concatenate the recommended convolutional code with one of the Reed-Solomon codes. Since this option is not considered by IOAG nor by LunaNet [5, 6] specifications, it is not discussed here as well.

4.2.1 CCSDS Convolutional Code

In coding theory, a convolutional code is a type of error correcting code which generates the codeword by applying a sliding window to the input stream of bits and computes the parity bits by combining various subsets of bits in this window.
In general, a rate $r = l/n$ convolutional encoder is a linear finite-state machine with l binary inputs, n binary outputs, and an m-stage shift register, where m is the memory of the encoder.

[2] Each PLTU contains a TF and Prox-1 TFs are of variable length as specified in section 3.1.1

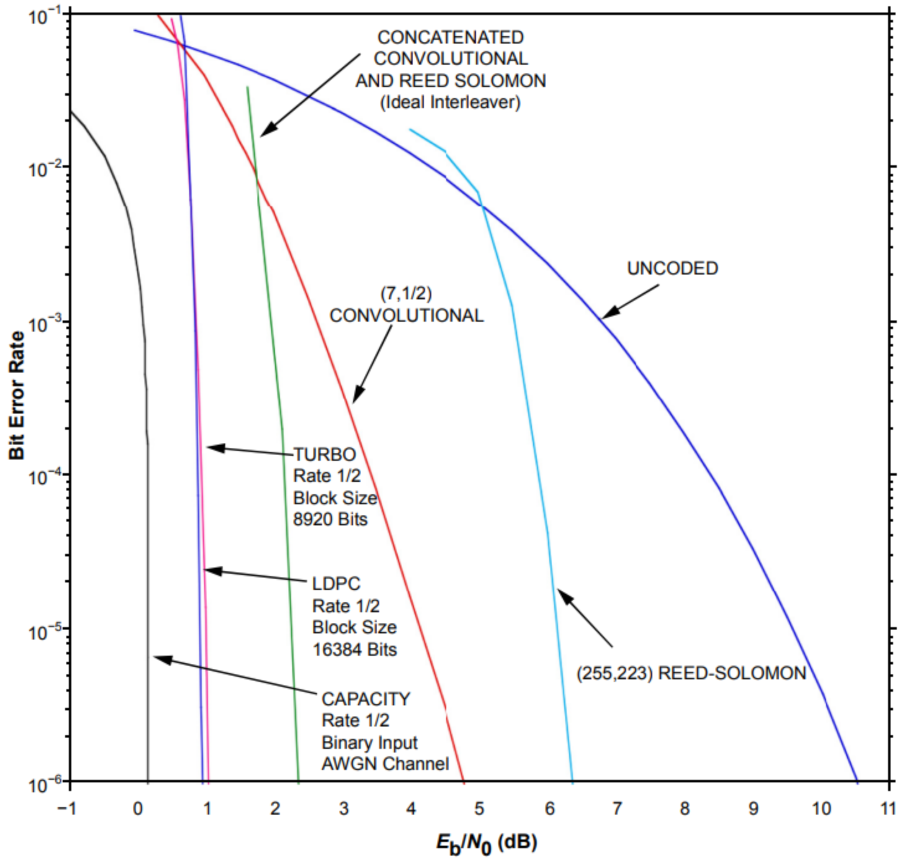


Figure 4.2: Performance comparison of several selected CCSDS coding schemes retrieved from [26]

The constraint length k of the convolutional code is defined as $k = m+1$, and the code is referred to as a (k,$^1/_n$) code.

The (7,$^1/_2$) convolutional code was selected in the 1970s for space applications by CCSDS. Exhaustive search over all convolutional codes with $r = {}^1/_2$ and $k \leq 7$ found that only this code (except for few symmetric equivalents) was able to achieve a minimum distance $d_{min} = 10$. Also codes with greater k values, e.g., (8,$^1/_2$) code, can only match the recommended (7,$^1/_2$) code's $d_{min} = 10$. Maximizing the minimum Hamming

distance d_{min} is an important consideration because the BER of a convolutional code with maximum likelihood decoding[3] falls off exponentially with d_{min} at low error rates. It is also important to achieve a good d_{min} at a reasonably low value of constraint length k because every unitary increase in k doubles the number of encoder states and therefore doubles the complexity of maximum likelihood decoding.
The recommended (7,1/2) code has another feature that makes it useful for space applications: it is transparent. Transparency means that at steady-state, if the input sequence to the encoder is inverted, the output will be inverted also. Similarly, if the input sequence to the decoder is inverted, at steady-state the output sequence of the decoder will be inverted too. This feature is useful because with Binary Phase Shift Keying (BPSK) modulation there is often a 180-degree phase ambiguity, and the demodulator can produce the inverse of the transmitted symbols even when it is in lock. With a transparent code, when the demodulator produces the inverse of the transmitted symbols, the decoder produces the inverse of the encoded bits.
The encoder for the CCSDS standard convolutional code is extremely simple. This means that the encoder can be made small and that it dissipates very little power. These are good attributes for spacecraft hardware.
Given its characteristics, both IOAG and LunaNet recommendations [5, 6] include the (7,1/2) convolutional code among the suggested options. While IOAG proposes its employment for low data rate missions only, LunaNet recommend its usage for both very low (0.048 Mbps) and higher (up to 5 Mbps) data rates.

4.2.2 CCSDS LDPC Codes

Low Density Parity Codes codes are a class of capacity-approaching error correcting codes that were invented by Gallager in 1961 during its PhD studies [27]. Technology of those years did not allow for their useful and efficient implementation, hence they were set aside for more than

[3]Accomplished by using the Viterbi algorithm for convolutional codes.

30 years. They were re-discovered in the mid-1990s thank to the discovery of an iterative decoding algorithm, called Belief Propagation, which achieves near-optimum performance for large linear LDPC codes at a feasible complexity. Since then it has become one of the most efficient and diffuse coding schemes being widely used in a large range of communication systems, like satellite communications (DVB-S2 or CCSDS) and mobile communications (5G).

LDPC codes are a class of linear block codes[4] whose parity check matrix **H** is sparse, i.e., it contains a very small number of ones with respect to its total size and this is the reason for the utilization of the name *low density*. This peculiarity provides big advantages during LDPC iterative decoding. The LDPC codes suggested by CCSDS are quasi-cyclic. Their parity check matrices are defined as a juxtaposition of smaller cyclic submatrices, known as circulants. A circulant is a square matrix of binary entries, in which each row is a one-position right cyclic shift of the previous one. Thus, the entire circulant matrix is determined by its first row, and low-weight circulants are used to define parity check matrices with low density.
Since these LDPC codes are quasi-cyclic, LDPC codewords require randomization in order to minimize the probability of false synchronization due to potential symbol slips. When LDPC coding is used, this is achieved using a pseudo-randomizer: a random sequence is exclusively ORed with the LDPC codewords to increase the frequency of bit transitions.

The LDPC coding schemes foreseen in the CCSDS reference standard [18] are divided in two families:

- a single high rate code with rate $r = 223/255 \simeq 7/8$ to be used in the Near-Earth region, where high datarates require fast encoding and decoding procedures. This code is designed to perform a low number of decoding iterations

[4] In coding theory a block code is an error correcting code which encodes data in blocks. The *linear* attribute indicates that any linear combination of codewords is also a codeword.

- a family of nine Accumulate, Repeat-by-4, and Jagged Accumulate (AR4JA) codes with rates $r = 1/2, 2/3, 4/5$. These codes are recommended to be used in the deep space case, where signals must travel large distances requiring good resistance to Signal-to-Noise Ratio (SNR) degradation. Hence, these codes have greater redundancy parts and are optimized for working at low E_b/N_0. This set of codes have three possible info block length $k \in \{1024,4096,16384\}$.

The $(n = 2048, k = 1024)$ rate $1/2$ code is the one recommended by Proximity-1 standard [19].
However, for Lunar proximity links between orbital assets and Lunar users, in addition to the code proposed by Prox-1, IOAG and LunaNet [5, 6] also add all the other LDPC codes suggested by CCSDS. As for the convolutional code, between the two there is a difference: the first does not specify any block length k; the latter, depending on the target data rate, considers only a subset of the available block lengths k.
The reason for these discrepancies from the reference standard will be explored in more detail in the section 5.1.1.

Chapter 5

Physical Layer

In the introduction (section 1.1) it was stated that this work would have had the focus on the Physical Layer and specifically on the realization of a multi-user architecture based on a FDM scheme rather than on TDM. In this regard, it must be mentioned that the Prox-1 standard protocol proposes a TDM approach. However, it should be more correctly called *time sequenced* approach, since it envisions the establishment of a link session with one asset first, and then establishing a second session with a second asset once the first has ended its communication needs. This proposal does not fit ANDROMEDA requirements. Also a more rigorous TDM scheme with shorter time slots has to be excluded since it implies a precision timing and synchronization, which in turn would require assets to have unfeasible complexity and managements needs. In support of this decision is also the IOAG document [5] that as alternatives to accommodate multiple simultaneous accesses does not include TDM. Furthermore, the recommendation foresees the possibility that for K-Band high rate proximity links, multiple access may be achieved by phased array antennas, i.e., with beamforming.
As an alternative to FDM, IOAG proposes the Code Division Multiplexing (CDM) scheme. However, at the present day, CDMA codes to be adopted for data communication only in space are not defined and hence are not available for an implementation in the coming few years which is contrast with ANDROMEDA deployment plan. Furthermore, codes assignment would require international coordination leading to more complex

architecture management even from a bureaucratic point of view.

5.1 Reference Recommendations and Standards

In a context of growing interest in the stable presence of humans in space, it becomes necessary to have standards and recommendations, otherwise it would be almost impossible for everyone to succeed in accomplishing anything. Specifically, with regard to communications in the Lunar environment, reference must be made to the Recommendation SFCG 32-2R3 [3] which (in accordance with ITU recommendations) puts guidelines for frequencies utilization in the Lunar region. The frequency allocation scheme of interest for this study, pointed out by SFCG, is reported in Table 5.1. From frequencies allocation table it is particularly interesting to notice that the recommended ones to be used on the Lunar surface (Lunar Surface Wireless Network) are the same currently utilized on Earth by the most used and famous communication wireless standards, i.e., Wi-Fi (short-range wireless network), LTE and 5G (short-to-medium range wireless network with mobility and roaming), as previously mentioned in section 3.1.
This frequency assignment recommendation is the document on which LunaNet and IOAG recommendations are based. As already mentioned in section 2.1, IOAG report [5] accurately summarizes all frequencies, modulations, and coding schemes which have been used and are planned to be used for all missions during the 2018-2030 timeframe. In addition to that, it provides hints for more detailed analysis concerning some key issues identified throughout their investigation. The report also envisions a possible interconnected communication scheme, some possible protocol stack implementations, and Lunar relay services.
LunaNet [6] is not intended to replace the IOAG document. It provides the minimum set of standard services and interfaces that will be available to Lunar users, such that users may design their systems with the expectation of available providers. For the compliance to LunaNet, individual provider is not required to offer all the proposed services and interfaces,

Table 5.1: SFCG allocation of frequencies of interest for ANDROMEDA architecture in the Lunar region

Link	**Frequency**	
Earth to Lunar Orbit	2025-2110	MHz
	7190-7235	MHz
	22.55-23.15	GHz
	40.0-40.5	GHz
Lunar Orbit to Earth	2200-2290	MHz
	8450-8500	MHz
	25.5-27.0	GHz
	47-38	GHz
...		
Lunar Orbit to Lunar Surface	390-405	MHz
	2025-2110	MHz
	23.15-23.55	GHz
Lunar Surface to Lunar Orbit	435-450	MHz
	2200-2290	MHz
	27.0.-27.5	GHz
Lunar Surface Wireless Network	390.405	MHz
	410-420	MHz
	435-450	MHz
	2.400-2.480	GHz
	2.5035-2.620	GHz
	5.15-5.835	GHz
	25.25-25.5	GHz
	27.225-27.5	GHz
...		

but the goal is that the aggregation of providers will have the interfaces and services described. LunaNet is intended to allow many Lunar mission users to engage the services of diverse commercial and government service providers in an open and evolvable architecture. LunaNet main goal is to provide to Lunar users an operational environment similar to that experienced by internet users on Earth. As such, it specifies all the element constituting a framework of mutually agreed-upon standards, protocols, and interface specification that enable interoperability. Along all the mentioned aspects, it also specifies working frequencies, modulations, coding schemes, and concept of operation to be adopted by service provider like ANDROMEDA is.

The main reference standards are those provided by CCSDS mentioned in section 3.1.1 on which the recommendations cited above are based.

5.1.1 Center Frequency and Frequency Bands

From Table 5.1, it can be noticed that the chosen working frequencies for ANDROMEDA (S-Band and K-Band, as discussed in section 2.2) are compliant to SFCG recommendation. Specifically, the frequency bands allocated for ANDROMEDA satellites communication DWE are those in the K-Band, i.e., 22.55-23.15 GHz for the forward link and 25.5-27.0 GHz for the return link. Also the frequency bands identified to be used for proximity links are compliant to SFCG allocations. Indeed, frequencies to be used by ANDROMEDA for communications towards the Lunar surface are the S-Band (2025-2110 MHz for the forward link and 2200-2290 MHz for the return link) and again the K-Band (23.15-23.55 GHz for the forward link and 27.0-27.5 GHz for the return link). For this thesis it was chosen to focus on the S-Band. The reasons behind this choice will be detailed in chapter 6.

The Proximity-1 has been considered and chosen to be the reference protocol for both the Coding & Synchronization Sublayer and the Physical Layer for ANDROMEDA proximity links. However, in section 4.2.2 some discrepancies between the Prox-1 protocol specifications and the reference

recommendations were highlighted. This is because the protocol was designed to work at UHF frequency band (390-405 MHz forward link and 435-450 MHz return link) at low data rates in deep space scenarios. As stated in section 2.2, among the services ANDROMEDA provides there is the exchange of video, voice, and generic data with Earth in a near real-time working mode. This specific operational mode envisages medium-to-high and high-to-very high data rates, hence UHF frequency band it is not suitable due to its lower achievable maximum data rate. This trend to higher data rates needs can also be noticed from both IOAG[1] and LunaNet specifications which exclude that frequency range among the suitable ones to be used by proximity links, even if present in SFCG frequency allocation plan. This trend can also be appreciated by looking at Table 2.1 where only one among the possible set of users for ANDROMEDA services lists UHF among the available communication frequencies.
However, an adaptation of Proximity-1 protocols [16, 19, 20] for the use of Lunar missions in S-Band (and K-Band too) is currently under consideration. NASA and all the world's major space agencies and companies are pushing for the implementation of this adaptation. Therefore, this work considered the protocol recommendations for the S-Band as existing *de facto*.

Referring to Table 5.1, it is possible to retrieve the available band in each listed frequency range. Among them, only the ones in the S- and K-Band are of interest. Thus, it is easy to see that for ANDROMEDA proximity links useful bandwidths are:

- 85 MHz (S-Band forward link)
- 90 MHz (S-Band return link)
- 400 MHz (K-Band forward link)
- 500 MHz (K-Band return link)

[1] In IOAG's document the UHF frequency range is allowed but limited to communications to and from the Lunar surface and hence not for any proximity link

As it can be observed, the higher frequency band has 5 times more available bandwidth than the lower one. This mainly implies the possibility to reach much higher data rates, justifying the choice about its usage especially for real-time video and audio data streams. A further limitation in the S-Band is dictated by the limitation imposed by the standard maximum bandwidth for non-spread spectrum signals which is fixed to be 5 MHz at most per user [6], imposing an upper bound to the achievable data rate. In fact, let's recall the Nyquist formula for a noise-free channel:

$$C = 2B \log_2(m) \tag{5.1}$$

where C is the channel capacity, B the channel bandwidth and m the modulation cardinality. Clearly, being the capacity and the available band directly proportional, at higher frequencies the achievable data rate is undoubtedly higher. One of the main reasons why in the S-Band there is little bandwidth available is that this specific frequency range is already very congested since a lot of already operative satellites communicate in that frequency band. Moreover, many different communication systems are allocated to the S-Band too. It is therefore a strict requirement to be able to use the least possible bandwidth in the most efficient way and this is where modulations come in handy.

5.1.2 Modulation Schemes

Modulation is the process in which a carrier signal is varied according to the information bearing signal also called the modulating signal. A carrier is a waveform, usually sinusoidal, which does not carry any information, but has a much higher frequency than the input signal and which has to be transmitted. The purpose of the carrier is to transmit information through a transmission medium (space in this case) as an electromagnetic wave. The information can be modulated on the carrier by affecting at least one of its characteristics such as phase, frequency or amplitude. Traditionally, by using many carriers at different frequencies it is also possible to transmit many signals on the same physical channel. This is the principle behind the Frequency Division Multiplexing scheme. As will be explained in detail in section 5.2, this work did not follow this traditional principle.

The LunaNet Interoperability Specification [6] has been the main guideline for modulations, as the document contains a very detailed section concerning all link interfaces specifications among all the possible network users which includes working frequencies, symbol rates, and modulations. Of particular interest for this thesis is the one named "*LNSP*[2]*-User Proximity Interfaces*". Specifically, it is useful because it is divided into sections based first on the working frequency, then based on the forward/return link, and finally based on data rates.
According to Lunar users data rates needs in S-Band, the identified reference LunaNet interfaces are the Proximity Forward S-Band Data Only (PFS1a) and the Proximity Forward S-Band High Rate Data Only (PFS1d). Their major characteristics are here reported:

- PFS1a:
  - Symbol rate: $2\,\text{ksps} \leq R_s \leq 2\,\text{Mbps}$
  - Modulation: BPSK
- PFS1d:
  - Symbol rate: $1\,\text{Msps} \leq R_s \leq 5\,\text{Mbps}$
  - Modulation: filtered OQPSK/GMSK

A general description of the modulations mentioned is given below.

BPSK

Binary Phase Shift Keying is the simplest among the Phase-Shift-Keying modulation family. As the word *binary* suggests, the number of possible phases that the carrier wave can assume is equal to two, separated by 180°. Bits transmitted with value 0 will hence be mapped to one of these two phases, while bits equal to 1 will be mapped to the other phase.
Since for each bit one symbol is transmitted, the symbol rate R_s will be

[2]LunaNet Service Provider

equal to the data rate R_b.
A Binary Phase Shift Keying signal can be analytically expressed as:

$$x(t) = \sqrt{2P_T}\cos(2\pi f_c t + \pi d(t)) \tag{5.2}$$

where f_c is the carrier frequency, P_T is the transmitted power, and $d(t)$ represents the binary input data stream. The Binary Phase Shift Keying constellation with the corresponding bit mapping suggested by CCSDS standard is shown in Figure 5.1.

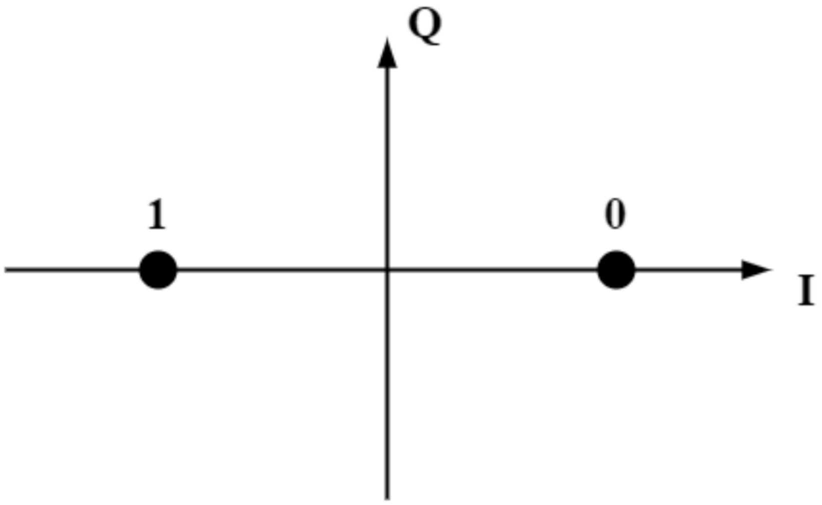


Figure 5.1: Mapping for the BPSK constellation

OQPSK

Orthogonal Quadrature Phase Shift Keying modulation is a modified version of QPSK modulation.
QPSK is a Phase Shift Keying modulation in which the carrier wave can have four different phase values, separated by 90°. These phases are associated to points in the complex plane according to the constellation mapping suggested by CCSDS, which is shown in Figure 5.2.

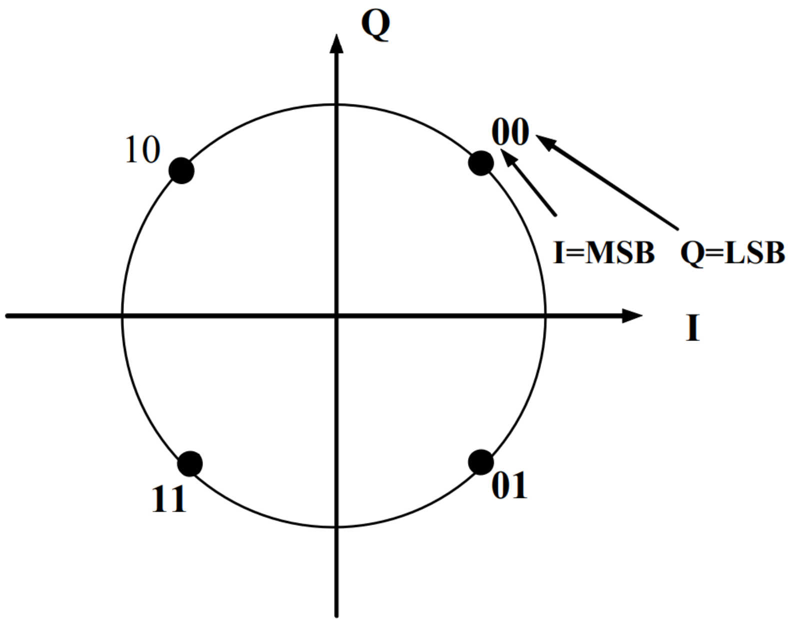


Figure 5.2: Gray mapping for the QPSK constellation

The analytical expression of a QPSK modulated signal is:

$$x(t) = \sqrt{\frac{2E_s}{T_s}} \cos(2\pi f_c t + \phi(t)) \tag{5.3}$$

where

$$\phi(t) = \frac{\pi(2i-1)}{4}, \quad i = 1,2,3,4 \tag{5.4}$$

and the value of i is chosen according to Table 5.2.
Since the modulator is able to encode two bits in each symbol, the modulated symbol rate R_s is the half of the data rate R_d. This implies that a QPSK modulator can transmit the same amount information with half of the bandwidth with respect to a BPSK modulator or, equivalently, twice as much information with the same bandwidth. That's why this modulation has been selected by LunaNet for the interface at higher symbol rates.
Going back to OQPSK description, as in QPSK case, the carrier wave can assume the same four different phase values. However, in OQPSK modulation the variation is limited to $\pm\pi/2$. Practically, phase changes of

Table 5.2: Mapping between QPSK bit pattern and phases

Pattern	i	$\phi(t)$
00	1	$\pi/4$
10	2	$3\pi/4$
11	3	$5\pi/4$
01	4	$7\pi/4$

$\pm\pi$ are eliminated introducing half symbol time delay in the quadrature component with respect to the in-phase component. Doing so, prevents both components to change simultaneously. This situation is pictorially represented in Figure 5.3, comparing QPSK and OQPSK cases.

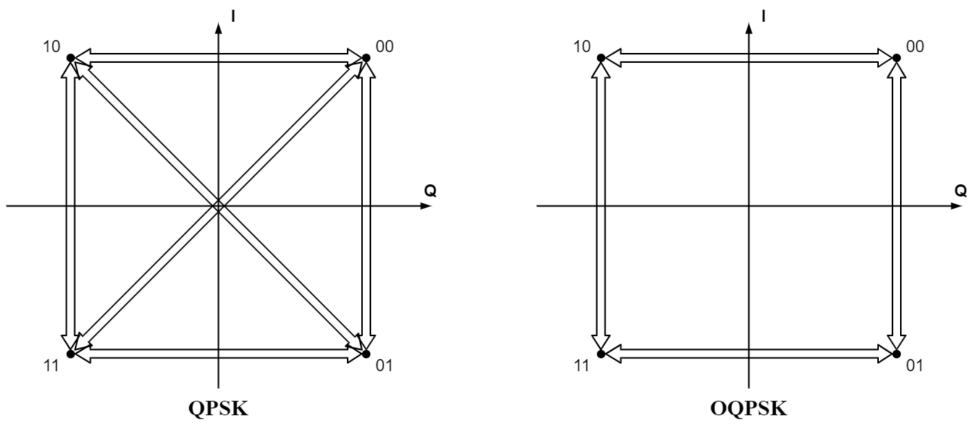


Figure 5.3: Possible phase changes in QPSK and OQPSK

GMSK

Gaussian Minimum Shift Keying (GMSK) is a highly bandwidth-efficient constant envelope and continuous phase modulation scheme first introduced in 1981 for communications in the 900 MHz and mobile radio environment. It is derived from Minimum Shift Keying (MSK) with an additional baseband Gaussian filter that further attenuates side lobes and reduces spectral bandwidth. MSK is a continuous phase modulation scheme and this implies that there are no phase discontinuities in the modulated signal: frequency changes occur at the carrier zero crossing points.
Similarly to OQPSK, MSK modulates the signal by mapping bits to in-phase and quadrature components and the quadrature component is delayed by half the symbol time. The difference between the two is that in MSK bits are encoded as half sinusoids, while OQPSK encode bits as square pulses.
One of the MSK's drawbacks is having a spectrum with side bands extending beyond a bandwidth matching the data rate. This unpleasant effect can be reduced by low-pass filtering the input signal before applying it to the carrier. When this filter is Gaussian, the modulation becomes a Gaussian Minimum Shift Keying (GMSK).
The main advantage of GMSK over OQPSK modulation scheme is that not only the phase change is limited to $\pm\pi/2$ in a bit interval but most importantly it is also linear. The linearity in the phase change allows to obtain power spectral density with low side lobes, condition useful to limit adjacent-channel interference. As a side effect, the main lobe becomes wider than the OQPSK one.
The modulation has been adopted by CCSDS as a standard for space missions due to its compact power spectrum and its high immunity against interference.
Analytically speaking, GMSK modulated signal can be expressed as:

$$x(t) = \sqrt{2P_T}\cos(2\pi f_c t + \phi(t)) \tag{5.5}$$

with

$$\phi(t) = \sum_{k=-\infty}^{\infty}\left(a_k\frac{\pi}{2}\int_{-\infty}^{t-kT_s} g(\tau)d\tau\right) \tag{5.6}$$

where a_k are the input symbols to be transmitted.
$g(t)$ is the instantaneous frequency pulse that can be obtained through a linear filter with impulse response given by the convolution

$$g(t) = h(t) * rect\left(\frac{t}{T_s}\right) \tag{5.7}$$

where

$$rect\left(\frac{t}{T_s}\right) = \begin{cases} \frac{t}{T_s} & |t| < \frac{T_s}{2} \\ 0 & Otherwise \end{cases} \tag{5.8}$$

and $h(t)$ is the Gaussian filter impulse response.

5.2 Synthesizer

In a standard Frequency Division Multiplexing scheme, each of the inputs modulate different carriers so that the modulated signals are in different frequency bands without interfering with each other (if needed a frequency guard could be used to make sure of this). A basic FDM scheme is depicted in Figure 5.4.

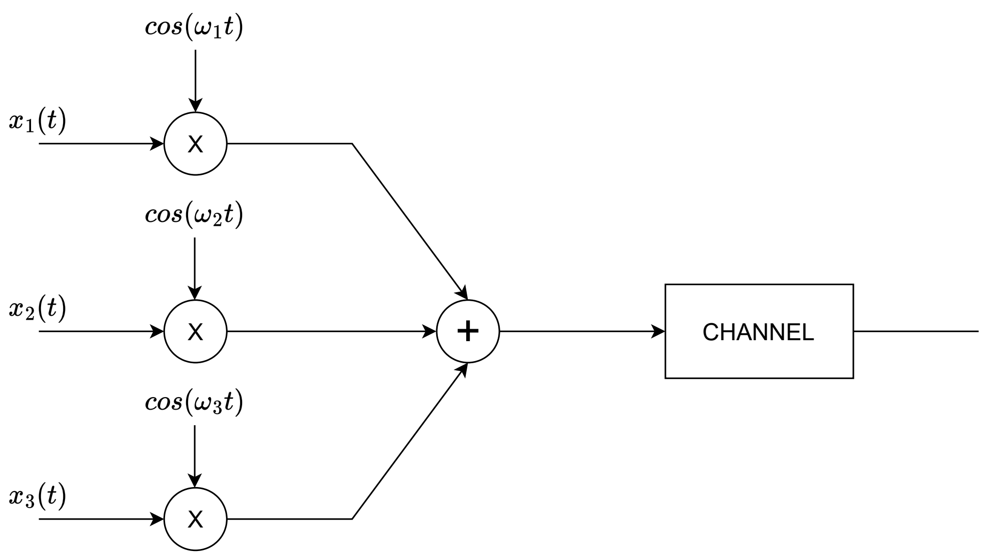


Figure 5.4: Frequency Division Multiplexing basic scheme

This frequency-multiplexed transmitter scheme has however some drawbacks: it implies the utilization of an high number of components (potentially expensive since they must be suitable for space grade) on electronic boards. Moreover, it should be remembered that in section 5.1.1 was mentioned that the available bandwidth in the S-Band is limited to be 5 MHz at most per user.
Therefore, following a deeper investigation of the subject it was chosen to implement a *synthesizer*. Normally, a synthesizer is identified as an electronic circuit that generates a range of frequencies from a single reference one. In this specific case, the term it is used to describe an element that upsamples and recomposes signals by means of a *synthesis* filter bank, as will be further discussed in section 5.2.1. Also in this thesis work, however, the synthesizer general meaning previously reported gives a very broad overview of its functioning. In fact, the element, given a set of narrowband input signals, is able to evenly spread them across the spectrum, separating them in the frequency domain. Specifically, it considers the bandwidth of each input signals and arranges them in the spectrum so that they remain side by side, each having its own central frequency. At this point it must be mentioned that at the synthesizer output is placed a low-pass Finite Impulse Response (FIR) filter which is able to efficiently cut the input signals in such a way that they do not create Interchannel Interference (ICI). This last peculiarity is of particular interest since it allows to constrain input signals bandwidth in an excellent way. As such, having strict limitations to be met regarding the per user bandwidth, it was one of the main drivers for the choice of a synthesizer over other possible implementations.
Another significant decision driver was the very small number of components needed to efficiently implement a synthesizer with respect to the most general case depicted in Figure 5.4. Moreover, by cleverly exploiting Field-Programmable Gate Array (FPGA) hardware capabilities it is possible to achieve very high data rates [28].
It was previously mentioned that the synthesizer takes narrowband signals as inputs. To that, it must be added that for the ANDROMEDA chosen communication scenario, input signals are also at baseband, since the constellation satellites act as regenerative nodes: a satellite transponder

may receive signals and retransmit them at higher power and at a different frequency, without any other processing and, additionally, it can also perform signal processing (i.e. demodulation of the carrier to baseband, regeneration of signals, and modulation). Therefore, especially in the store & forward operational mode, every relay satellite will have data at baseband. The regenerative approach has several advantages at the expenses of greater implementation complexity. For instance, it improves channel efficiency (an important characteristic due to the high bandwidth demand in space communications), enhances the system capacity and reduces errors in the communications increasing the system reliability. Moreover, a regenerative payload provides compliance with the DTN, which is the baseline protocol stack selected for ANDROMEDA.
In the following is given a detailed analytical description of the synthesizer implemented for this work (section 5.2.1) and the main working parameters for its correct functioning are described.

5.2.1 Synthesizer Description

The element takes its name from filter banks' reconstruction process called *synthesis*.

Traditionally, the synthesis filter bank consists of a set of parallel bandpass filters that merge multiple input narrowband signals, $x_0[m], x_1[m], \cdots x_{(M-1)}[m]$ into a single output broadband signal, $y[n]$. The input narrowband signals are in the baseband. Each narrowband signal is interpolated to a higher sampling rate by means of up samplers, and then filtered by low-pass filters. A complex exponential that follows low-pass filters centers the baseband signal around the desired center frequency f_c. Finally, signals are all summed together and transmitted. A conceptual block diagram is shown in Figure 5.5.

The synthesis filter bank can be efficiently implemented using a polyphase structure (taking as a reference a polyphase interpolator)[3]. To derive it,

[3]Analytical derivations are from [29]

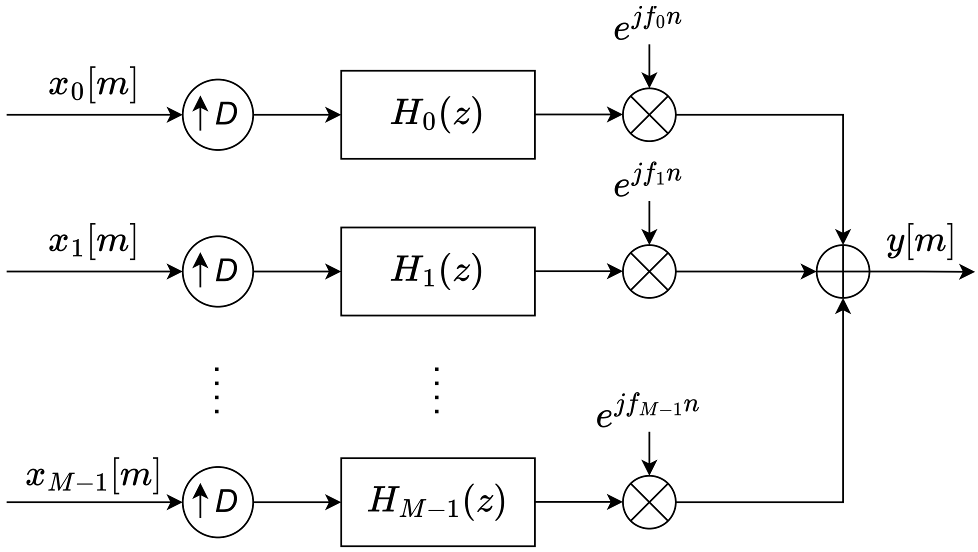


Figure 5.5: Synthesis filter bank conceptual diagram

let's start with the transfer function of a (digital) low-pass filter of length N:

$$
\begin{aligned}
H(Z) &= \sum_{n=0}^{N-1} h(n) Z^{-n} \\
&= h(0) + h(1)Z^{-1} + h(2)Z^{-2} + \cdots + h(N-1)Z^{-(N-1)}
\end{aligned}
\tag{5.9}
$$

Equation 5.9 is the Z-transform of the standard FIR filter structure presenting a set of delayed filter coefficients. Then, partitioning the same filter into M-parallel filter paths (which are the number of polyphase components i.e., branches) it is possible to map the filter transfer function from a one-dimensional array of weights (filter taps) to a two-dimensional array (the filter is basically represented as a sum of successively delayed sub-filters with coefficients separated by M samples):

$$
\begin{aligned}
H(Z) = h(0) + h(M+0)Z^{-M} + \cdots + h(N-M)Z^{-(N-M)} \\
+h(1)Z^{-1} + h(M+1)Z^{-M+1} + \cdots + h(N-M+1)Z^{-(N-M+1)} \\
+h(2)Z^{-2} + h(M+2)Z^{-M+2} + \cdots + h(N-M+2)Z^{-(N-M+2)} \\
\vdots \\
+ h(M-1)Z^{-(M-1)} + h(2M-1)Z^{-(2M-1)} + \cdots + h(N-1)Z^{-(N-1)}
\end{aligned}
\tag{5.10}
$$

This two-dimensional array is hence loaded by column but processed by rows in the polyphase representation. In fact, it can be noticed that the first row in Equation 5.10 is a polynomial in Z^M, which can be denoted as $E_0(Z^M)$. The second row it is not a polynomial in Z^M but it can be made into one by factoring the common Z^{-1} term and identifying this row as $Z^{-1}E_1(Z^M)$.
It is straightforward to see that each row of Equation 5.10 can be described as $Z^{-r}E_r(Z^M)$ so that it is possible to compact it as:

$$
H(Z) = E_0(Z^M) + Z^{-1}E_1(Z^M) + \cdots + Z^{-(M-1)}E_{M-1}(Z^M) \tag{5.11}
$$

where $E_0(Z^M), E_1(Z^M), \ldots, E_{M-1}(Z^M)$ are polyphase components of the filter (filter taps for each branch).
Considering Figure 5.5 and imposing $H(Z) = H_0(Z)$, all the other filters $H_k(Z)$, where $k = 1, \ldots, M-1$, composing the filter bank are modulated versions of the just analyzed one.

In the representation of Figure 5.5, signals reaching filters are zero-packed time series due to up samplers. However, zeros in the series do not contribute to the weighted sums[4] formed at the filter output. Since they do not contribute, there is no need to perform the product sum from the input data having the known zero-valued samples. Thus, we can track their location in the filter and perform the weighted sum only for useful samples. These values are exactly separated by D samples, i.e., the up

[4] Convolution between filter taps and input signal

sampling factor, and their position shifts through the filter as each new zero-valued input is presented to the input of the filter. Keeping track of the coefficient stride and the position of each coefficient set is automatically performed by the polyphase partition of the filter. This structure enables the application of the *noble identity*.
The noble identity is compactly represented in Figure 5.6 and states that the output from a filter $H(Z^M)$ preceded by an 1-to-D up sampler is identical to an 1-to-D up sampler preceded by a filter $H(Z)$. For computation simplicity let's consider $D = M$, i.e., the up sample factor equal to the number of polyphase branches of the filter. The proof of this principle can

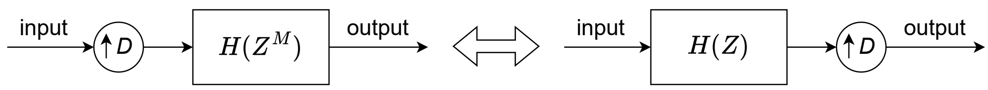
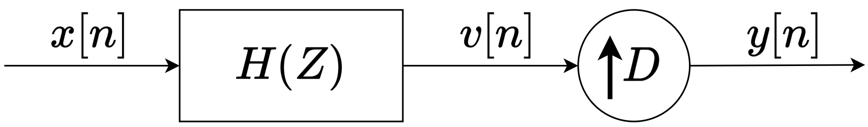


Figure 5.6: Noble identity for interpolator

be easily derived exploiting the Z-transform. Consider the following block diagram:



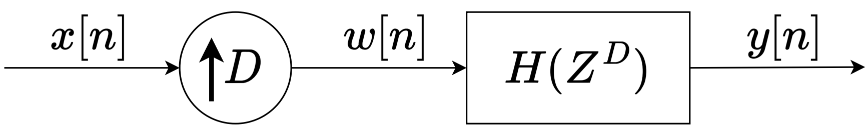
Using the Z-transform it is possible to perform simple analytic computations from which follows

$$V(Z) = H(Z)X(Z) \qquad \text{and} \qquad Y(Z) = V(Z^D)$$

and thus,

$$Y(Z) = H(Z^D)X(Z^D)$$

Consider now the opposite diagram:



It follows that

$$W(Z) = X(Z^D) \qquad \text{and} \qquad Y(Z) = H(Z^D)W(Z)$$

Consequently,

$$Y(Z) = H(Z^D)X(Z^D)$$

By applying the noble identity to the block diagram represented on the left side of Figure 5.7, it is possible to move resamplers following each separate filter stage so that they up sample each time series by a factor $D = M$. Delays in every arm shift each resulting time series by a different time increment so that only non-zero samples reach the summing junction at the output. Therefore, an output commutator is introduced so that the arm sequentially points to the branch supplying a non-zero sample, rather than performing the sum with multiple zeros every time. This final configuration is shown on the right side of Figure 5.7.

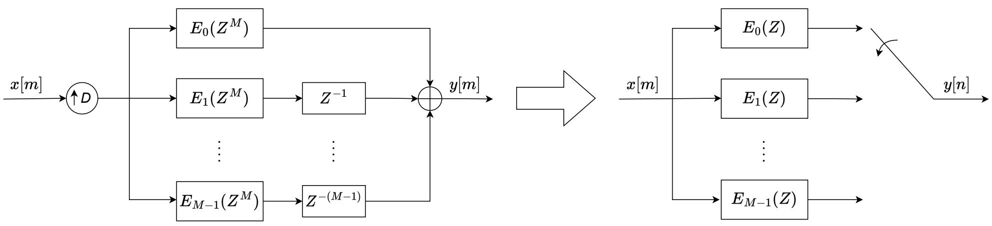


Figure 5.7: Example of noble identity application to a low-pass polyphase filter (polyphase interpolator)

Let's now recall that the purpose of interpolation process was to raise the input sample rate to allow the translation of the input spectrum to an higher frequency.
The digital processing described and applied above creates aliases of the input time streams, that reside at multiples of the input sample rate. With a traditional signal processing the low-pass FIR filter would reject the spectral copies, conserving only the baseband one. Exploiting the frequency translation property of the Z-transform[5] it is possible to convert a low-pass filter to a band-pass filter associating the complex terms of the modulation process of the filter weights with the delay elements storing

[5]If the impulse response $h(n)$ of a low-pass filter has Z-tranform $H(Z)$ then the impulse response of a band-pass filter $h(n)e^{+j\theta n}$ has Z-transform $H(Ze^{-j\theta n})$

the filter weights. In this way, rather than extracting the spectral copy at baseband from the replicated set of spectra we can directly extract one of the spectral translates by using a band-pass filter as opposed to a low-pass filter. Hence, the general transfer function (5.11) of the k-th modulated band-pass filter can be written as

$$\begin{aligned} H_k(Z) &= H(Ze^{jn\omega_k}) \\ &= E_0(Z^M) + Z^{-1}E_1(Z^M)e^{j\omega_k} + \cdots + Z^{-(M-1)}E_{M-1}(Z^M)e^{j(M-1)\omega_k} \end{aligned} \tag{5.12}$$

where $n = 0, \ldots, M-1$ and $\omega_k = 2\pi k/M$ with $k = 0, \ldots, M-1$.
As a consequence, the transfer function $H(Z)$ for all M channels in the filter bank in its polyphase and matrix form can be written as:

$$H(Z) = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & e^{j\omega_1} & \cdots & e^{j(M-1)\omega_1} \\ \vdots & \vdots & \cdots & \vdots \\ 1 & e^{j\omega_{(M-1)}} & \cdots & e^{j(M-1)\omega_{(M-1)}} \end{bmatrix} \begin{bmatrix} E_0(Z^M) \\ Z^{-1}E_1(Z^M) \\ \vdots \\ Z^{-(M-1)}E_{M-1}(Z^M) \end{bmatrix} \tag{5.13}$$

Combining the use of a band-pass filter and the effects of the noble identity it is possible to rewrite in a simpler way the transfer function $H(Z)$ of Equation 5.13 for all the M channels in the filter bank:

$$H(Z) = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & e^{j\omega_1} & \cdots & e^{j(M-1)\omega_1} \\ \vdots & \vdots & \cdots & \vdots \\ 1 & e^{j\omega_{(M-1)}} & \cdots & e^{j(M-1)\omega_{(M-1)}} \end{bmatrix} \begin{bmatrix} E_0(Z) \\ E_1(Z) \\ \vdots \\ E_{M-1}(Z) \end{bmatrix} \tag{5.14}$$

Eventually, it can be noticed that the matrix on the left is an IDFT matrix, therefore an efficient implementation of the synthesizer can be made exploiting the IFFT algorithm implementation. The overall structure of the synthesizer is finally represented Figure 5.8, where each input $x_0[m], x_1[m], \cdots x_{(M-1)}[m]$ represents a different communication channel.

Summarizing, the synthesizer structure has been derived starting from a typical FDM scheme, substituting the low-pass filter bank with a polyphase

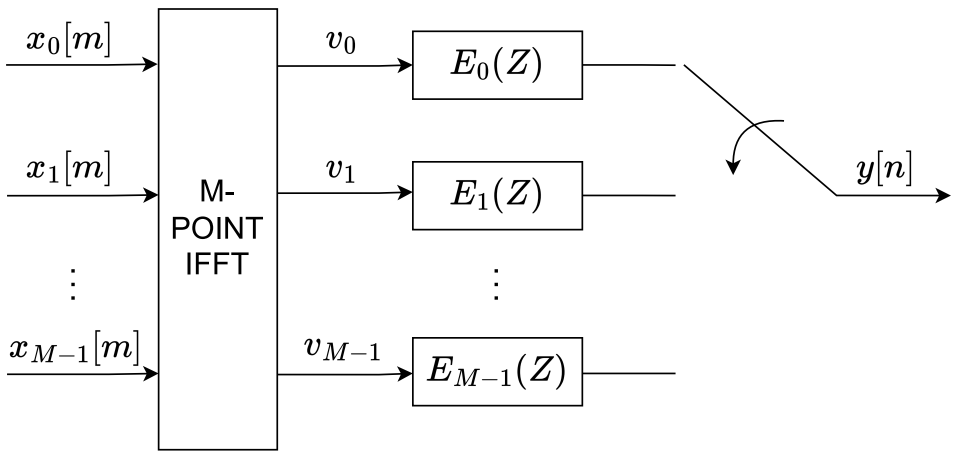


Figure 5.8: Polyphase synthesizer schematic

structure and thus obtaining a more efficient implementation.

Clearly, the parameters characterizing the synthesizer are input and output rates, and the output filter. Observing Figure 5.9, the output rate can be easily identified to be

$$R_{out} = MR_{in} \tag{5.15}$$

where the synthesizer input rate R_{in} is equal to the sampling frequency ($f_s = R_{in}$), i.e., the rate at which a new symbol reaches the IFFT block. It is also important to highlight that the output filter must be designed to have both adequate cutting frequency and stop band attenuation, and its sampling frequency must be at least equal to the channel sample rate, i.e., R_{out}. All these parameters depend on implementation choices such as the number of input channels and will hence be better described and justified after the discussion about test architecture definition and setup in section 6.3.

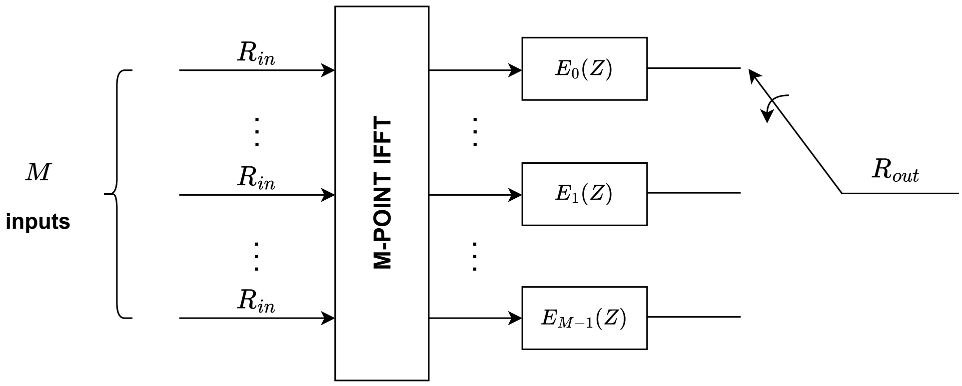


Figure 5.9: Synthesizer characteristic parameters

Chapter 6

Implementation, Tests, and Results

Previous chapters discussed the parameters, limitations, recommendations, and reference standards that guided the design of ANDROMEDA multi-user architecture at the Data Link and Physical Layers. Here instead implementation choices and strategies are analyzed, a test bench architecture is defined together with all the related parameters, and tests results are eventually reported.

6.1 Test Architecture

[redacted]

6.1.1 Multiplexing Structure Consolidation

[redacted]

[redacted]

Figure 6.1: Combined multiplexing stages of Data Link and Physical Layers

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

6.1.2 Comprehensive Test Architecture

[redacted]

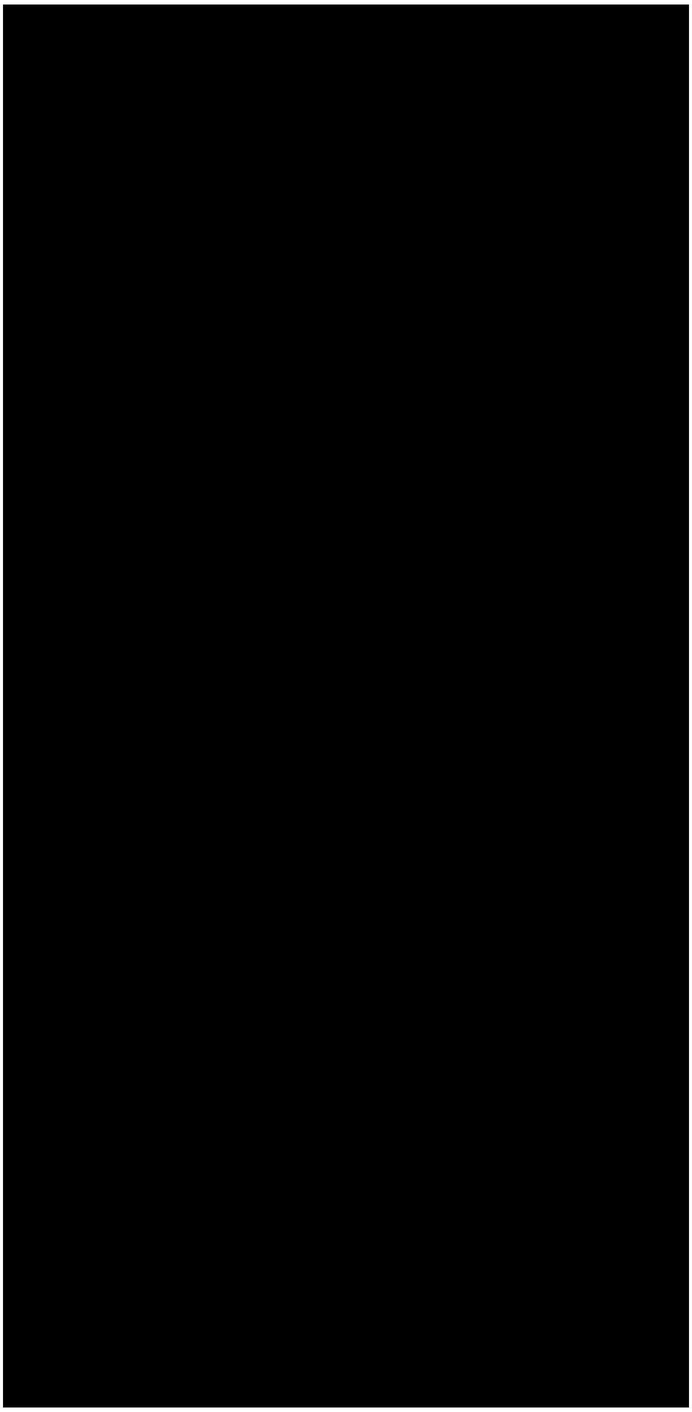


Figure 6.2: Ideal test architecture schematic

[redacted]

6.2 Test Bench Setup

[redacted]

- [redacted]
- [redacted]

[redacted]

Figure 6.3: Test bench setup with instruments and connections

[redacted]

- [redacted]

[redacted]

6.3 Implementation Choices and Software Limitations

[redacted]

6.3.1 Physical Layer Implementation

[redacted]

- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]

[redacted]

[redacted]

Figure 6.4: Comparison between the spectrum of the output signal of a custom implemented and a MATLAB-implemented synthesizer

[redacted]

[redacted]

[redacted]

[redacted]

6.3.2 Parameters Definition

[redacted]

[redacted]

[redacted]

[redacted]

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[redacted]

- [redacted]
- [redacted]
- [redacted]

- [redacted]

[redacted]

Low-Pass Output Filter

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

(a)

[redacted]

(b)

Figure 6.5: Impulse (a) and frequency (b) responses of the synthesizer low-pass output filter

6.4 Test Report

[redacted]

[redacted]

[redacted]

Figure 6.6: Schematic of the architecture implemented and tested

[redacted]

[redacted]

[redacted]

6.4.1 Tests Description

[redacted]

[redacted]

Table 6.1: Tests list with relevant parameters

[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted] [redacted]	[redacted] [redacted]
[redacted]	[redacted]	[redacted] [redacted]	[redacted] [redacted]
[redacted]	[redacted]	[redacted] [redacted]	[redacted] [redacted]
[redacted]	[redacted]	[redacted] [redacted]	[redacted] [redacted]
[redacted]	[redacted]	[redacted] [redacted]	[redacted] [redacted]
[redacted]	[redacted]	[redacted] [redacted] [redacted]	[redacted] [redacted] [redacted]
[redacted]	[redacted]	[redacted] [redacted] [redacted]	[redacted] [redacted] [redacted]

[redacted]

6.4.2 Tests Results

[redacted]

[redacted]

Figure 6.7: Test [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Figure 6.8: Test [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Figure 6.9: Test [redacted]

[redacted]

[redacted]

Figure 6.10: Test [redacted]

[redacted]

(a)

(b)

Figure 6.11: [redacted]

[redacted]

[redacted]

[redacted]

(a)

[redacted]

(b)

Figure 6.12: [redacted]

[redacted]

[redacted]

[redacted]

Figure 6.13: Test [redacted]

[redacted]

[redacted]

(a)

[redacted]

(b)

Figure 6.14: [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Figure 6.15: Test [redacted]

[redacted]

Figure 6.16: Test [redacted]

[redacted]

[redacted]

Figure 6.17: Test [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted] [redacted]

[redacted]

Figure 6.18: Test [redacted]

[redacted]

Chapter 7

Final Remarks

7.1 Conclusions

This thesis work proposed the design of a end-to-end multi-user architecture for Lunar proximity links, with a focus on the forward and specifically on the link between a spacecraft and users in the Lunar region.
After the definition of the most suitable protocol stack for the specific scenario, the multiplexing procedures and strategies to be adopted at the Data Link Layer were refined.
Given the objective difficulties related to the implementation of a new communication protocol, it was decided to focus on the study and implementation of the Physical Layer. An FDM approach was chosen because it represents an innovative aspect for space communication and given the advantages this strategy offers in terms of system complexity.
A frequency synthesizer in its polyphase form was designated to be the multiplexing element to be implemented at the Physical Layer. After its detailed study, its validation in a communication chain was performed using MATLAB. Subsequently, it was implemented in *C++*.
To validate the designed Physical Layer multiplexing strategies tests were performed by means of a Software Defined Radio and the resulting output analyzed exploiting a spectrum analyzer. Analysis were performed considering different modulation schemes and different data rates to prove the system capabilities.

7.2 Future Developments

Several natural continuation of the work carried out in this thesis are possible. As a first thing the software implementation of the synthesizer can be improved and optimized, thus allowing to perform more test including coding too. For example, a possible big improvement can be the implementation of a multi-thread software, as mentioned earlier in section 6.4. Then, the entire Data Link Layer together with the multiplexing strategies defined in this work have to be implemented.
Following these mentioned works, many other can follow as the implementation of the synthesizer on a Field-Programmable Gate Array (FPGA) so that higher data rates can be achieved.

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