Protocol Proximity-1 Simulator for Telemetry on Mars Missions

Francisco Fraga Barros Barbosa da Maia

Thesis to obtain the Master of Science Degree in

Electrical and Computer Engineering

Supervisors:
Prof. José Eduardo Charters Ribeiro da Cunha Sanguino
Prof. António José Castelo Branco Rodrigues

Examination Committee:

Chairperson: Prof Paulo Luís Serras Lobato Correia
Supervisor: Prof António José Castelo Branco Rodrigues
Member of the Committee: Prof Francisco Bucho Cercas

January 2021

Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Declaração

Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e Boas Práticas da Universidade de Lisboa.

Acknowledgements

Firstly, I would like to express my sincere gratitude to both my IST supervisors, Prof. António Rodrigues and Prof. José Sanguino, for their tremendous support, dedication and availability. I also wish to express my appreciation to Instituto de Telecomunicações for suggesting the theme of this dissertation and for the resources made available.

I would also like to express gratitude to Eng. Tiago Hormigo from Spin.Works for the interest shown in this thesis and for his availability during my research.

I would like to acknowledge the unconditional support provided by my family during the whole preparation of this thesis, I would like to thank my mother and father for always believing in me, for encouraging me to always go further in life and pursue my dreams. We share great values and an eternal bond, my twin brothers, João and Pedro for showing me how to be persistent and to never be afraid of going after our life goals. My grandmother for raising a joyful and united family. Mafalda for showing me that it is possible to go for spectacular trips around the world while being at a demanding course, and finally my cousin António for being a tremendous help since the beginning of my course.

Lastly, I would like to thank all my friends, which I am so grateful to have. Miguel, thank you for your unquestioning friendship since we were kids. Afonso, Francisco, Inês, Maria, Pedro and Sebastião thank you for sharing with me the passion for great adventures that are much needed in my days. Madalena, we all have that person who is willing to go the extra mile for others without asking for anything in return, thank you for being that person. Madalena, I wish everyone has a special person in their lives as you have been in mine.

Abstract

“Mankind is drawn to the heavens for the same reason we were once drawn into unknown lands and across the open sea. We choose to explore space because doing so improves our lives, and lifts our spirit. So let us continue the journey”– George W. Bush.

The race for space exploration has been increasing substantially, following the rapid technological development in recent years. In 2013, the Consultative Committee for Space Data Systems (CCSDS), formed by numerous space agencies - such as China National Space Administration (CNSA), Federal Space Agency (FSA), European Space Agency (ESA) and National Aerospace and Space Administration (NASA) – recommended a new standard protocol for space communications between spacecrafts in close proximity. This protocol is called Proximity-1 Space Protocol.

Proximity-1 describes recommendation standards for the two lowest layers of the Open Systems Interconnection (OSI) Model – Data Link Layer and Physical Layer. Both layer recommendation will be taken into consideration in this simulator.

The purpose of this work is to simulate data transfer between two space vehicles (orbiter, lander or rover) according to the Proximity-1 Space Link Protocol and draw conclusions regarding its performance – percentage of error frames received, modulation and demodulation processes, data flow between sublayers, as well as its processing times, among others. Moreover, one could simulate any vehicle (orbiter, lander or rover) that needs to comply with the Proximity-1 standards.

The simulation allows analyzing in detail the proximity-1 protocol operations and interoperability between sublayers, contributing for a better understanding of each process. With this simulator, it is possible to adjust the protocol different parameters - transmission power of each space vehicle, signal to noise ratio of the transmission channel, number of samples per bit, filters applied in the demodulation process, among others. Moreover, the simulation enables the flow of data, analyzing each step of the process, since the formation of a data packet, converting it into a modulated signal and vice-versa.

Regarding the Physical Layer, a Binary Phase Shift Keying (BPSK) modulator and demodulator are presented. The demodulator was tested in three different ways: using a *Costas Loop* algorithm, a *Phased Locked Loop* algorithm and an adaptation of the *Phased Locked Loop*. The main goal is to synchronize the frequency and phase of the receiving signal that suffers interference, and hence receive the transmitted data seamlessly.

Unlike the Physical Layer, the Data Link Layer is made up of separate blocks – sublayers – that cooperate to transform the received bitstream into data and vice-versa. Each block is asynchronous and has its own processing time that operates independently in a non-sequential order. Each sublayer has its own task: decode the received bits, group them into frames, monitor them, and give internal directives. These two layers are the backbone of protocol Proximity-1 Simulator.

Keywords: BER, BPSK, Costas Loop, Data Link Layer, demodulator, frame, lander, modulator, Phase Locked Loop, Physical Layer, rover, orbiter, transceiver.

Resumo

“A Humanidade é atraída para o espaço pela mesma razão que fomos atraídos por terras desconhecidas. Optámos pela exploração espacial uma vez que melhora as nossas vidas e dá-nos ânimo. Assim, continuaremos a aventura.” – George W. Bush

Hoje em dia, a corrida pela exploração do espaço tem vindo a aumentar substancialmente, beneficiando do rápido desenvolvimento tecnológico ao longo dos anos. No ano de 2013, foi criado um protocolo pelo *Consultative Committee* for *Space Data Systems* (CCSDS) que conta com prestigiadas agencias espaciais, entre elas a *China National Space Administration* (CNSA), *Russian Federal Space Agency* (FSA), *European Space Agency* (ESA) e *National Aerospace and Space Administration* (NASA). Este protocolo designa-se como Protocolo Proximity-1, que define normas na comunicação entre um satélite e um lander com relativa proximidade. *Proximity-1* descreve recomendações para as duas camadas inferiores do modelo de *Open Systems Interconnection* (OSI) - camada de dados e camada física. A recomendação de ambas as camadas será tomada em consideração nesta simulação.

O objetivo deste trabalho é simular a transferência de dados entre dois veículos espaciais (*orbiter*, *lander* ou *rover*) de acordo com o protocolo espacial *Proximity-1* e tirar conclusões relativamente ao seu desempenho - percentagem de *frames* recebidas com erro, processos de modulação e desmodulação, fluxo de dados entre subcamadas, bem como seus tempos de processamento, entre outros. Além disso, pode-se simular qualquer veículo (*orbiter*, *lander* ou *rover*) que deva cumprir com os requisitos do protocolo.

A simulação permite analisar detalhadamente as operações do protocolo *Proximity-1* e a interoperabilidade entre subcamadas. Esta simulação permite ajustar os diferentes parâmetros do protocolo - potência de transmissão de cada veículo espacial, relação sinal / ruído do canal de transmissão, número de amostras por bit e filtros aplicados no processo de desmodulação. A simulação possibilita analisar as várias etapas do fluxo de dados, desde a formação de um pacote de dados e conversão num sinal modulado e vice-versa.

Em relação à camada física, um modulador e desmodulador *Binary Phase Shift Keying* (BPSK) são apresentados. O desmodulador foi testado de três maneiras diferentes: usando um algoritmo *Costas Loop*, um algoritmo *Phased Locked Loop* e uma adaptação do *Phased Locked Loop*. O objetivo principal é sincronizar a frequência e a fase do sinal de receção que sofre interferência e, portanto, receber os dados transmitidos sem erros.

Ao contrário da camada física, a camada de dados é composta por vários blocos separados - subcamadas - que cooperam para transformar o fluxo de bits recebido em pacotes de dados e vice-versa. Cada bloco é assíncrono e tem seu próprio tempo de processamento que opera de forma independente. Cada subcamada tem a sua própria tarefa: descodificar os bits recebidos, agrupá-los em *frames*, monitorizá-los e fornecer diretivas internas. Estas duas camadas são a espinha dorsal do simulador do protocolo Proximity-1.

Palavras-chave: BER, BPSK, camada física, camada de tratamento de dados, Costas Loop, desmodulador, frame, lander, modulação, Phase Locked Loop, rover, satélite.

Contents

List of Figures

List of Tables

List of abbreviations and acronyms

ASM	Attached Synchronization Marker
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CCSDS	Consultative Committee for Space Data Systems
CCITT	Consultative Committee for International Telephony and Telegraph
COP	Communication Operations Procedure
CRC	Cyclic Redundancy Check
DFC ID	Data Field Construction Identifier
ESA	European Space Agency
FARM	Frame Acceptance and Reporting Mechanism
FOP	Frame Operation Procedure
IESS	Intelsat Earth Station Standards
MAC	Medium Access Control
MER	Mars Exploration Rover
MEX	Mars Express
MIB	Management Information Base
OBC	On Board Computer
OSI	Open Systems Interconnection
P-frame	Protocol Data Frame
PCID	Physical Channel Identifier
PLCW	Proximity Link Control Word
PLTU	Proximity Link Transmission Unit
QoS	Quality of Service
SCID	Spacecraft Identifier
SPDU	Supervisory Protocol Data Unit
U-frame	User Data Frame

Definitions

Bitstream - Stream of data in binary form.

Communication Channel (or Communication Link) - Physical connection between two transceivers in a communication session.

Communication Session - Time period during which two transceivers are communicating with each other.

Data Link Layer - Second layer of the Open System Interconnection (OSI) Model.

Data Packet - Unit of data made into a single package that travels a given network path.

Full Duplex Operation - Both transmitter and receiver are active at the same time in a transceiver.

Half Duplex Operation - The transceiver switches between using its transmitter and receiver during a communication session.

Hailing - Activity used to establish a Proximity link with a remote vehicle. Hailing requires the use of a hailing frequency pair (bidirectional). Either element can initiate hailing. The process is done at a low data rate and therefore is a low bandwidth activity. The first-generation transceivers are fixed frequency and use Channel 0.

Lander - Spacecraft that descends towards, and comes to rest on, the surface of an astronomical body.

MATLAB - Software developed by MathWorks.

On-Board Computer - Computer system that the Proximity-1 module is connected to which configures the Proximity-1 module.

Orbiter - Spacecraft design to go into orbit, especially one that does not subsequently land.

Physical Layer - The lowest layer of the Open System Interconnection (OSI) Model.

Protocol Data - Information and commands consumed within the Proximity-1 protocol.

Protocol Data Packet - Data Packet which contains protocol data.

Protocol frame (P-frame) - Transfer frame containing protocol data.

Proximity Link Control Word (PLCW) - Protocol data unit which is used in the COP process to send the status of received Sequence Controlled frames.

Rover - Planetary surface exploration device designed to move across the solid surface on a planet or other planetary mass celestial bodies.

Signal to noise ratio - Measurement of signal strength relative to background noise.

Simplex operation - Only the transmitter or only the receiver is active in a transceiver during a communication session.

State diagram - Diagram used in computer science to describe the behavior of a system considering all the possible states of an object when an event occurs.

Supervisory Protocol Data Unit – structure of data used by the transceiver to control or to report status to the remote transceiver. This Data Unit contains one or more directives, reports or PLCWs.

User data - data provided to the Proximity-1 module from the local On-Board Computer and sent to the remote On-Board Computer.

User data packet - Data packet which contains user data.

User frame (U-frame) - Transfer frame containing user data.

Version-3 Transfer Frame – data structure that consists of a frame header and payload data, which is used to transfer data between two Proximity-1 transceivers.

Transceiver – space vehicle that can both transmit and receive communications, for example an orbiter a lander or a rover.

1. Introduction

1.1. Context

This section presents a first background analysis about the importance of the Proximity-1 protocol.

“This year has also been an inflection point in aerospace, with NASA committing to send astronauts to the moon once again, government programs all around the world taking huge strides towards a new era of globalized space exploration” (TIME, July 8, 2019). Therefore, research and development of radio communications should keep up the same pace, as they have an important role in space exploration.

Short-range communications (surface-to-orbit) are necessary for data transfer between vehicles (rovers and orbiters). In previous space missions, there was a direct communication link between the rover and Earth, which meant a rover should be capable of transmitting data back to Earth. Furthermore, a rover had limited resources regarding the transmission rate and power consumption leading to the fact that data could be sent relatively slowly with a weak signal. In response, a new protocol was created. Protocol Proximity-1 was developed to establish a communications protocol among orbiters, landers and rovers.

For instance, data is transmitted from a rover to a lander, both on Mars surface, then to a Mars orbiter, that, in turn, transmits the information back to an Earth orbiter or directly to an Earth station on its surface. Thereby, the rover does not require a heavy structure neither computation complexity to ensure the transmission of data directly to Earth.

The information travels a shorter distance, from the rover to the lander and to the orbiting orbiter on Mars. This way, we mitigate the error rate and improve the bitrate, since an orbiter or a lander can have a more robust engineered structure to transmit data than a rover can.

Proximity-1 Space Link protocol approved by the Consultative Committee for Space Data Systems (CCSDS) is an important benefit for orbiters, landers and rovers, therefore improving future Mars explorations.

1.2. Scope of the Thesis

Protocol Proximity-1 is used for the communication between space vehicles (orbiter, lander and rover) that are relatively close in space. This protocol sets up and closes down a communication session, transmitting and receiving data during the session.

A communication session is the time period during which two transceivers are communicating with each other. In order to do so, this module must communicate effectively between the two Layers (Physical Layer and Data Link Layer). The Proximity-1 protocol consists of two parts, one part that handles the transmission of data, and another part that handles the reception of data.

From the sending side, the module must process all the commands generated in the Data Link Layer and convert them into a bit stream, which will be sent to the Physical Layer. This Layer is responsible for converting that data into a modulated signal to be sent to space and to be received by a remote transceiver. On the receiving side, the Physical Layer must convert the received modulated signal into a well-defined bit stream (without errors) which will be passed on to the upper layer - Data Link Layer, which will generate the necessary commands.

Protocol Proximity-1 consists of a Physical Layer and a Data Link Layer.

Data Link Layer, made up of five sublayers, is responsible for processing the data from the moment it is inserted by the On Board Computer in the Input/Output Sublayer, through Data Services Sublayer, Frame Sublayer until reaching the Coding and Synchronization Sublayer. All of them are influenced by the Medium Access Control Sublayer directives, before information is sent to the Physical Layer as a bitstream.

Subsequently, the Physical Layer is responsible for transforming the received bitstream into a modulated signal (electromagnetic wave) and sending it (on the sending side), as well as receiving an electromagnetic wave and transforming it into a stream of bits (on the receiving side) that will be sent to the Data Link Layer for decoding and processing of data.

The purpose of this work is to simulate data transfer between two space vehicles (orbiter, lander or rover) according to the Proximity-1 Space Link Protocol and draw conclusions regarding its performance – error frames received, modulation and demodulation processes, data flow and processing times between sublayers. Proximity-1 Data Link Layer and Physical Layer requirements will be taken into consideration in this simulation. Moreover, one could simulate any vehicle (orbiter, lander or rover) that needs to comply with the Proximity-1 standards.

1.3. Research Questions

This section enumerates the main guidelines for this work and tries to answer several questions.

Is the protocol flexible and robust enough to allow space communications? What are the different factors that affect a communication session? What is the benefit of a communications system with an intermediary (as the protocol Proximity-1) regarding a direct transmission from a rover to a satellite? How does fading affects the received signal? What is the interference caused by the Martian atmosphere? What is the attenuation caused by the different lines of sight between a lander a rover and an orbiter? What is the bottleneck affecting the protocol simulation? In which Sublayer does this bottleneck occur? What is the transmission efficiency of the simulator? What is the signal to noise ratio limit for the signal to be transmitted, error-free, across the transmission channel?

1.4. Document Outline

The document is organized into five chapters. In this introductory chapter, an overall context of the protocol Proximity-1 is presented. The scope, the objectives and the layout of the dissertation are also outlined.

Chapter 2 and 3 introduce the data processing layer and the physical layer, respectively. The second chapter also deepens its sublayers, the functioning and interoperability between them, according to the protocol rules. Chapter 4 describes the simulation that was developed, based on the protocol, detailing the Physical and Data Link Layers. This chapter explains the structure of the MATLAB simulation, the implemented functions and the data flow, ending with a brief state diagram.

Finally, chapter 5 presents the results and the conclusions drawn from this simulation and the main recommendations for future developments. The conclusion is described in chapter 6.

2. Proximity-1 Protocol Standard – Data Link Layer

2.1. Overview

The Proximity-1 protocol specifications can be found in CCSDS recommended standards [1], [2], [3] and [4].

“The Proximity-1 protocol is a bi-directional Space Link Protocol designed for the purpose of proximate communications among probes, landers, rovers, orbiting constellations, and orbiting relays” (*Source: [1]*). Data Link Layer and Physical Layer are two of the seven layers of the Open Systems Interconnection (OSI) model that are implemented in this protocol. Data Link Layer is divided into two parts, the sending side and the receiving side. Figure 2.1 shows an overall overview of the connections between all sublayers both from the sending and receiving side.

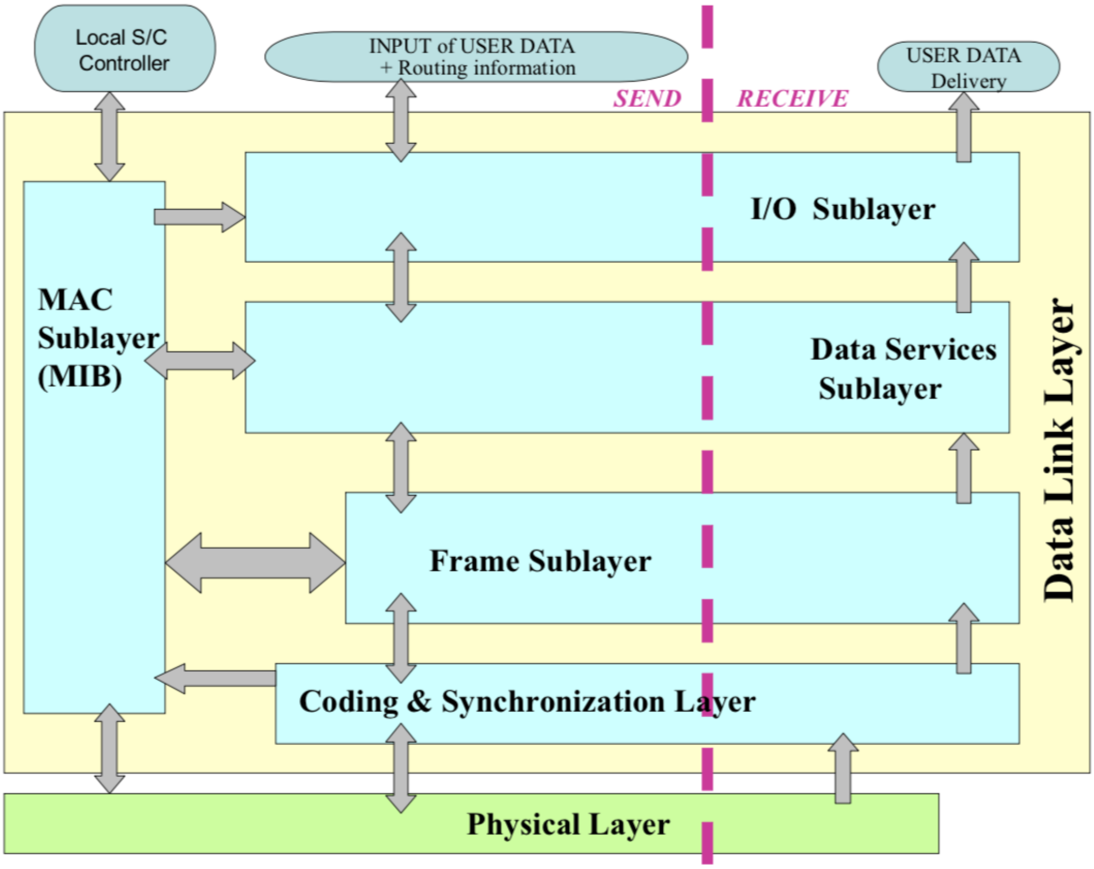


Figure 2.1 – Simplified diagram of Proximity-1 layers (source: [1]).

The sending side is responsible for the data processing since the input from the On Board Computer until sending a bitstream to the Physical Layer, while the receiving side receives a bitstream and converts it into data to be sent to the OBC. The Data Link Layer has 5 sublayers. The I/O Sublayer is responsible for the interface between the OBC and the Data Link Layer, by sending or receiving data packets from other sublayers, usually the Data Service Sublayer. This sublayer has the task to supervise the Communication Operation Procedure and to count the number of sent and received frames. Data Services Sublayer transmits its data to the Frame Sublayer that, in turn, selects a Version-3 Transfer Frame type. This procedure should be selected according to a priority list. The selected frame is then sent to the Coding and Synchronization Sublayer where an identifier called Attached Synchronization Marker (ASM) and a checksum (CRC) are attached to the transfer frame. The ASM, transfer frame and checksum form a data unit called Proximity Link Transmission Unit (PLTU). The PLTU will be sent as a bitstream to the Physical Layer to be converted into a modulated signal that can be transmitted through space by an antenna. The Medium Access Control Sublayer is connected to all sublayers and forwards directives.

According to the protocol, there are different types of data that are exchanged between sublayers. There are two types of Service Data Units, protocol-frames or user-frames. Protocol frames are used inside Proximity-1 protocol for configurations or directives, while user-frames contain data to be transmitted between transceivers. The I/O Sublayer receives Service Data Units and forms Version-3 Transfer Frames that has two separate fields: a transfer frame header and a transfer frame data field. The structure of a Version-3 Transfer Frame is shown in Figure 2.2.

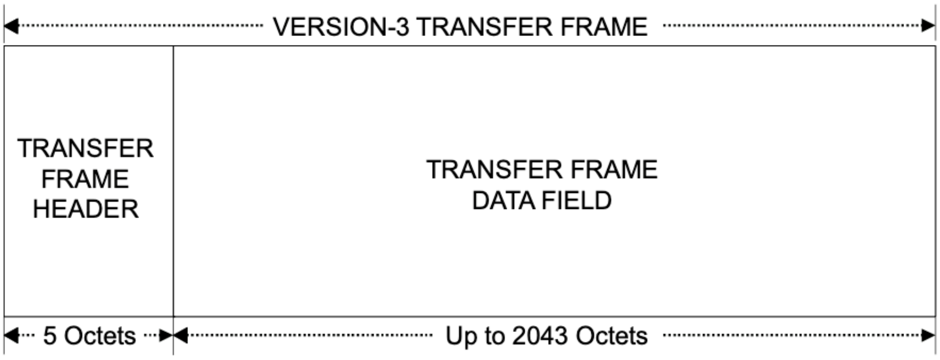


Figure 2.2 – Version-3 transfer frame (source: [2]).

The transfer frame header has ten fields, from the most significant bit (Transfer Frame Version Number) to the least significant bit (Frame Sequence number). Figure 2.3 represents the transfer frame header with the correspondent field bit length.

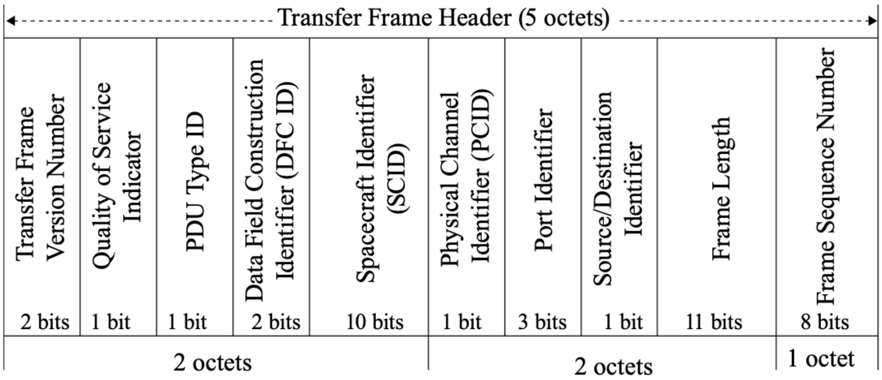


Figure 2.3 – Version-3 transfer frame header (source: [2]).

Transfer Frame Version Number is set to ‘10’ representing number 3 in binary, that stands for Version-3 Transfer Frame. The Quality of Service has only one bit allocated that is to indicate if a Frame is an Expedited Frame - ‘0’ or a Sequence Controlled Frame – ‘1’. The Protocol Data Unit Type ID with only one bit allocated specifies if the frame is a User Data Frame (U-frame) – ’0’ or if it contains a SPDU (Protocol Data Frame or P-frame) – ‘1’. The Data Field Construction Identifier (DFC ID) with two bits indicates the content of the Transfer Frame Data; if it is a P-frame then this field is not used therefore being ‘00’; if the content is a U-frame the DFC ID could be ‘01’ for segment data (a complete or segmented packet, ‘10’ is reserved for future CCSDS definition and ‘11’ for user defined data. The Spacecraft Identifier (SCID) is self-explanatory containing the source or destination spacecraft identifier and has 10 bits allocated. The Physical channel identifier (PCID) is used to distinguish between two transceivers, the sender and the receiver. An implementation can choose to ignore the PCID field. The Port Identifier indicates the port to which the I/O sublayer delivers a U-frame, in case it is a P-frame the Port ID is set to ‘0’. The Source/Destination Identifier indicates the contents of the SCID field whether it is a ‘0’ – source or a ‘1’-destination. The Frame Length indicates the length of the frame. Finally, the Frame Sequence Number increments the counter for both quality of service types. After the Version-3 Transfer Frame Header, the Transfer Frame Data field is concatenated and has variable length up to 2043 octets/bytes.

The Transfer Frame is converted into a Proximity Link Transmission Unit inside the Coding and Synchronization Sublayer by attaching an Attached Synchronization Marker (ASM) in the beginning of the frame and a Cyclic Redundancy Check (CRC) at the end. In fact, the PLTU as the name implies is the Data Unit base structure that is transmitted across space to the remote transceiver. Figure 2.4 represents the structure of a PLTU. This transmission unit might be encoded by the Coding and Synchronization Sublayer prior to the transmission, if required.

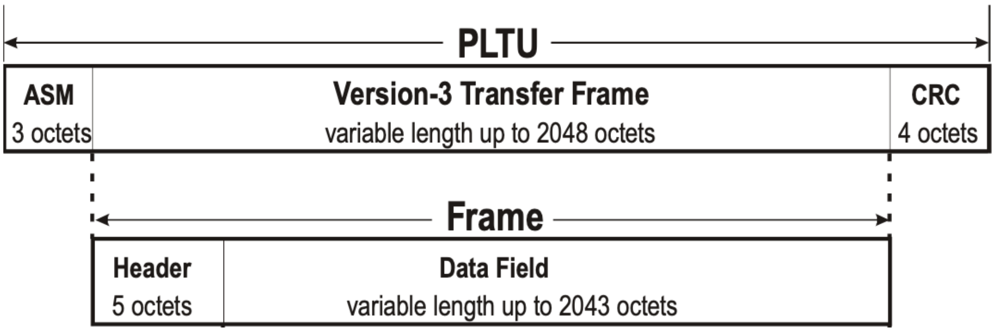


Figure 2.4 – Proximity link transmission unit structure (source [2]).

In addition, the frame that is sent inside the PLTU has a Quality of Service assigned. This is an important parameter that impacts the Communication Operations (COP) Procedure. There are two quality of services that a frame can have, the Expedited service and the Sequence Controlled service.

The Sequence Controlled service is more reliable than the Expedited service, as a result of using a go-back-n Automated Repeat Queuing (ARQ) algorithm. Moreover, this algorithm guarantees a correct reception, meaning that it requires the receiver to emit a message when a sequence controlled frame is received. This process is called the acknowledgement. On the other hand, Expedited services do not require any acknowledgement from the receiver. Nonetheless, the expedited quality of service has higher priority than a sequence controlled service on the frame selection process.

The following sections describe each sublayer, that constitute the Data Link Layer, in more detail.

2.2. Input/Output Sublayer

The I/O Sublayer is the interface between the On Board Computer and the Data Link Layer.

Additionally, on the sending side, this sublayer accepts the Service Data Units (SDUs) and its routing information arriving from the OBC and separates them into two buffers, that consequently will be received by the Data Services Sublayer. The two buffers are the Expedited buffer and the Sequence Controlled buffer. Also, the sending side notifies the OBC when an Expedited SDU is radiated, as well as when a Sequence Controlled SDU has been successfully transmitted across the communication channel to the remote transceiver.

Whereas, on the receiving side, the I/O Sublayer accepts the U-frames sent by the lower Data Services Sublayer and forwards them to the OBC. The I/O Sublayer only delivers complete SDUs and discards the incomplete or faulty. This is a concern for the Expedited frames: if they are lost, they will not be retransmitted, in contrast with the Sequence Controlled frames.

2.3. Data Service Sublayer

The Data Services Sublayer is responsible for the Communication Operations Procedure (COP) and this sublayer is between the I/O Sublayer and the Frame Sublayer.

On the sending side it is responsible for the Frame Operation Procedure for Proximity links, it receives Proximity Link Control Words (PLCW), which are the acknowledgements from the remote transceiver indicating it has received the Sequence Controlled Frame. This sublayer also counts frames that are sent and receives both Expedited and Sequence Controlled Frames.

On the receive side, the Data Services Sublayer runs the Frame Acceptance Reporting Mechanism (FARM) process and accepts User frames from the Frame Sublayer.

Communication Operations Procedure (COP), FOP and FARM Processes

The COP process requires two nodes, a sender and a receiver and a communication link established between them. The sender node transmits frames to the receiver, that in turn validates the Expedited frames and confirms if the Sequence Controlled frames arrive in sequential order. The receiver node gives feedback to the sender acknowledging the reception of a Sequence Controlled frame in a form of a PLCW. In case the PLCW has information to retransmit the last frame, the sender node must retransmit the last sent Sequence Controlled frame. This procedure does not apply to the expedited frames.

This process requires a bidirectional communication session established, each node has both sender and receiver functionality. The COP-P is represented in Figure 2.5.

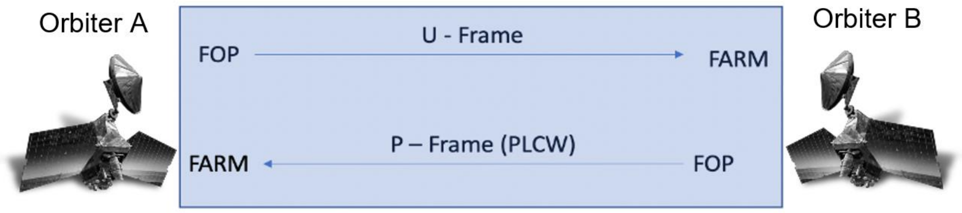


Figure 2.5 - COP-P process (source [2]).

If orbiter A wants to transmit a signal, it initiates the FOP process and sends a User Frame, whereas in orbiter B initiates the FARM process to receive the frame and report the acknowledgement in case the frame has a Sequence Controlled quality of service. The acknowledgement is sent from orbiter B to orbiter A in a form of a PLCW. During the FARM process, orbiter B checks if Sequence Controlled frames arrive in sequential order. If not, then the frame is discarded and the FARM process informs orbiter A (initiating a FOP process) of the frames it has accepted by sending a PLCW. Furthermore, the PLCW contains the sequence number of the next Sequence Controlled frame that should be transmitted or retransmitted next.

“Both the sender node and the receiver node contain two types of procedures, the send side procedures, i.e., the FOP-P and the receive side procedures, i.e., the FARM-P.” (*Source [5]*, page 4-7).

The FARM process simply reacts upon receiving a frame initiated by the transceivers FOP process and provides appropriate feedback via the PLCW. The Coding and Synchronization Sublayer plays an important role in order to check if a frame received is error free.

“The FOP-P and FARM-P procedures control both Expedited and Sequence Controlled qualities of service.” (*Source [5]*).

2.4. Frame Sublayer

The Frame Sublayer is responsible for selecting the frame for transmission according to a priority list and then appends the frame header to a SPDU data. This sublayer is located between the Data Services Sublayer and the Coding and Synchronization Sublayer.

From the sending side, the Frame Sublayer accepts frames supplied by the Data Services and MAC Sublayers and modifies field values as necessary, formulates PLCWs and status reports as needed and incorporates them into a P-frame, determinates the order of frame transmission and transfers the frames to the C&S Sublayer.

From the receiving side, the Frame Sublayer receives a frame from the Coding and Synchronization Sublayer, validates that the received frame is a Version-3 Transfer Frame, and also confirms that the frame should be accepted by the local transceiver based on the Spacecraft ID field and the Source-or-Destination ID of the transfer frame. If the frame is a valid U-frame, the Frame

Sublayer receiving side forwards it to the Data Services Sublayer. If the frame is a valid P-frame (also know as Supervisory Protocol Data Unit or Protocol Data Frame) and contains a PLCW, routes it to the Data Services Sublayer; if the frame is a valid P-frame but does not contain a PLCW, routes the content of the frame - directives - to the MAC Sublayer. (*Source* [2])

Frame Selection

The selection of each frame by the Frame Sublayer before sending it to the Coding and Synchronization Sublayer shall take into consideration the following priority:
1^{st} Priority: Frame from the MAC queue in the MAC Sublayer.
2^{nd} Priority: PLCW or status report, if the last frame sent was a U-frame.
3^{rd} Priority: Frame from the Expedited Frame queue.
4^{th} Priority: Sequence Controlled frame, first from the Sent queue if retransmission is required, and then from the Sequence Controlled Frame queue.
5^{th} Priority: PLCW or status report, if the last frame sent was not a U-frame.

2.5. Medium Access Control Sublayer

The MAC Sublayer provides directives to all sublayers part of the Data Link Layer. In fact, these directives are responsible for establishing or ending a communication session. Additionally, the directives contain configurations for the Data Link Layer and operational configurations for the Physical Layer.

Some of the operations performed by the MAC Sublayer require a “handshaking” process between the sending transceiver and the responding transceiver. This handshake is often based upon interpretation of values of the Physical Layer control signals, i.e., when a carrier signal is acquired and when symbol synchronization has been acquired.

2.6. Coding and Synchronization Sublayer

The Coding and Synchronization Sublayer is the interface between the Data Link Layer and the Physical Layer.

On the sending side, the Coding and Synchronization Sublayer is responsible for constructing PLTUs and converting them into a bitstream to be used in the Physical Layer. Each PLTU contains an Attached Synchronous Marker in the beginning, a Version-3 Transfer Frame, where the data is stored, and at the end has a Cyclic Redundancy Check to detect and correct some bit errors. The Version-3 Transfer Frame is delivered by the Frame Sublayer. After creating the PLTU the data structure is encoded if required. In case there is no Frame selected for transmission, the C&S Sublayer inserts Idle Data into the bitstream to be sent by the Physical Layer to the remote transceiver. The stream is provided at a constant rate to the Physical Layer for modulation onto the radiated carrier.

On the receiving side, the C&S Sublayer is responsible for the reception of the coded stream sent by the Physical Layer at a constant rate. This bitstream passes through a channel decoding and validates the PLTU. After removing the ASM and verifying any errors in the CRC process, a valid Transfer Frame is extracted and sent to the Frame Sublayer. In case the CRC detects an error, the C&S Sublayer shall mark the received frame as invalid. This Sublayer shall use the Frame Length field in the Transfer Frame Header of the Version-3 Transfer Frame to locate the position of the CRC-32 field of the PLTU. The CRC-32 marks the end of the PLTU, which can be followed by Idle data. The C&S Sublayer searches the received coded symbol stream following the end of the PLTU, looking for the ASM of the next PLTU, so any intervening idle bits are discarded.

Figure 2.6 represents the interactions between the C&S Sublayer upper and lower layers and the corresponding data.

While establishing a Proximity-1 session for a full-duplex or half-duplex link, synchronization is required for each PLTU. Therefore, when no PLTU is provided, Idle Data is selected for transmission, in order to maintain synchronization.

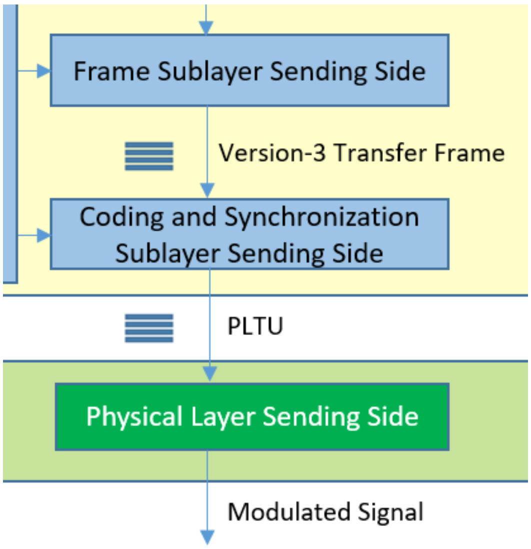


Figure 2.6 - Coding and synchronization sublayer sending side interactions.

2.6.1. Proximity Link Transmission Unit (PLTU)

The PLTU is a variable length data structure. A PLTU shall encompass the following three fields, positioned contiguously, as Figure 2.7 shows.

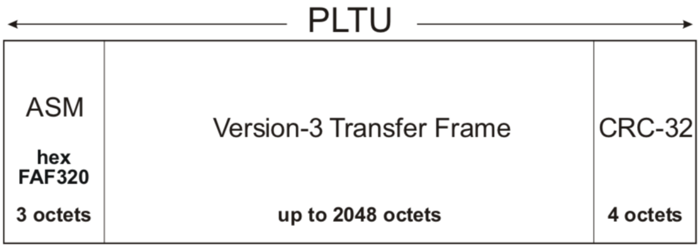


Figure 2.7 - Proximity-1 link transmission unit (PLTU) (source: [4]).

The length of a PLTU depends on the length of the transfer frame it contains. A PLTU can have a length up to 2055 (3 bytes for Attached Synchronization Marker, up to 2048 bytes for the Transfer Frame and 4 bytes for the Cyclic Redundancy Check).

The Attached Synchronization Marker (ASM), that occupies the first 24 bits of the PLTU, consists of the following bit pattern FAF320 (in hexadecimal). The ASM is used to detect the start of a PLTU.

Version-3 Transfer Frame contains data from the upper Sublayers.

Cyclic Redundancy Check immediately follows the Version-3 Transfer Frame and is calculated by applying the encoding procedure (specified in Annex C). Basically, the CRC consists of dividing the bits desired for encoding by a well-established polynomial (known by the two transceivers) and the remainder of this division is the bit structure that is attached to the Transfer Frame. Then the process repeats itself for the attached CRC, and the remainder of the division should be zero. If it is not zero, an error during transmission occurred. The ASM shall not be part of the encoded data space of the CRC-32. As shown in Figure 2.7, the CRC is part of the PLTU but is not part of the Version-3 Transfer Frame. In this respect, Proximity-1 differs from other CCSDS space data link protocols. (*Source [4]*)

2.6.2. Idle Data

Idle data is used under three circumstances: in the acquisition sequence, when there is no PLTU to be transmitted (called the idle sequence), and in tail sequence (before ending the transmission). These sequences (Acquisition, Idle and Tail) are specified in reference [4].

The Acquisition sequence is inserted in the beginning of a communication session, the Idle sequence corresponds to the sequence 352EF853 (in hexadecimal) that is transmitted when no PLTU is selected for transmission. In this case, the Idle sequence is injected into the bit stream to be encoded, in order to keep the channel symbols stream flowing and to enable the receiver to maintain synchronization.

When the ending of the sequence is reached, a new series of idle bits (Tail sequence) is transmitted, repeating the cycle. This process helps to maintain bit lock while it completes the processing of the final received data unit. The cycle continues until a PLTU is selected by the Frame Sublayer to be transmitted to the remote transceiver, after encoding in the Coding and Synchronization Sublayer and converted into a modulated signal by the Physical Layer.

2.6.3. Channel Coding

In protocol Proximity-1 there are three options for channel coding: Convolutional code, Low Density Parity Check (LDPC) – which is a Convolutional Code variant - or a no coding option. Some transceivers implement additional channel codes to those defined in the Proximity-1 recommended standards (such as the Reed-Solomon code).

The convolutional and LDPC codes are optional. The usage of the convolutional or LDPC code by the transmitter is configured by the directives from the MAC Sublayer, as well as decoding the transmitted frame on the remote transceiver receive side. The directives are defined in Annex A (see reference [2]). Figure 2.8 shows the procedures inside the Coding and Synchronization Sublayer. For more detailed information regarding both convolutional code and LDPC, see reference [4] in section 3.4.

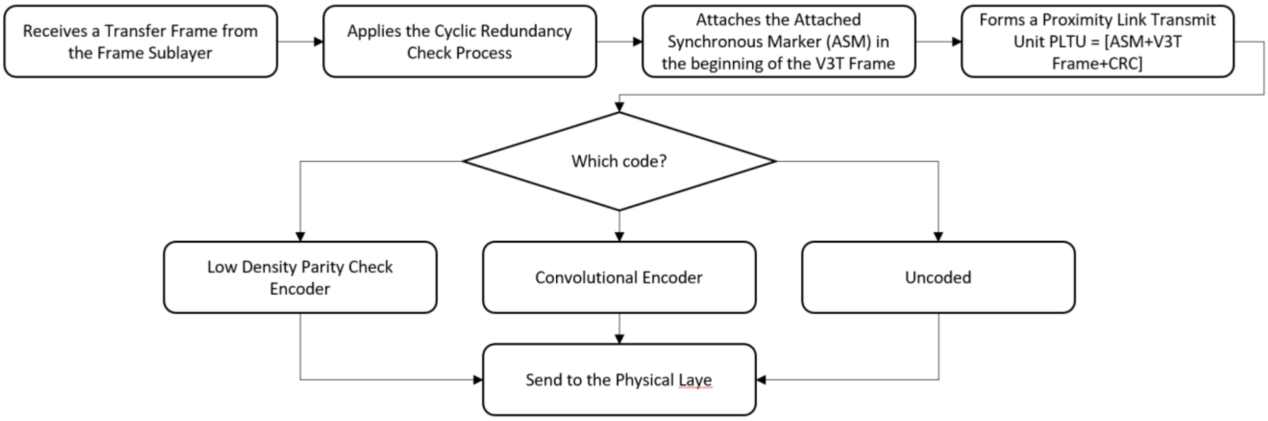


Figure 2.8 - Coding and synchronization sublayer (source [4])

3. Proximity-1 Protocol Standard – Physical Layer

3.1. Overview

The Physical Layer is the lowest layer on the OSI Model. This protocol also takes this last layer into consideration which is the backbone for establishing a communication session. The Physical Layer main purpose is to establish a communication channel between two transceivers by converting the serial bitstream, sent by the Coding and Synchronization Sublayer, into a modulated signal that, in turn, will be transmitted across space in a form of an electromagnetic wave as well as receiving the signal, demodulating it and converting it into a bitstream.

The Physical Layer also interacts with the MAC Sublayer, where it may receive four different directives (Mode, Duplex, Transmit and Modulation). Figure 3.1 represents the different interaction that Physical Layer has with the Data Link Layer both from the send and receive sides.

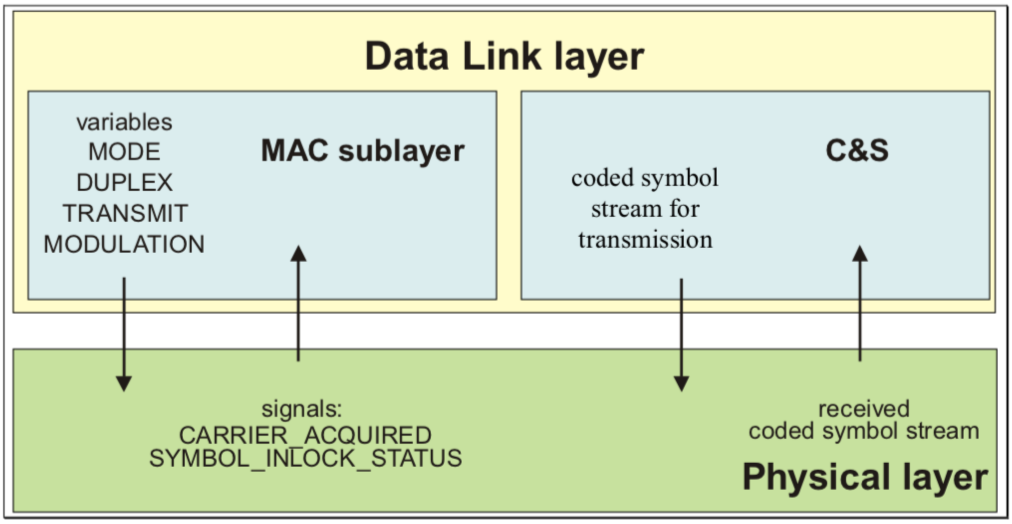


Figure 3.1 - Control variables, signals and data transfers (source [3]).

There are several parameters to configure the communication session, frequency, polarization, modulation, acquisition, idle sequence and the coded symbol rates. These operating characteristics are described in detail on the following sections.

3.2. Transmitter

The Physical Layer has three operational states from the sending side that influence the transmitter state, as shown in Table 3.1.

While establishing a Proximity-1 session for a full-duplex or half-duplex link, synchronization is required for each PLTU. Therefore, when no PLTU is provided, Idle Data is selected for transmission, in order to maintain synchronization.

Table 3.1 - Transmitter control variables (source [3])

MODE	TRANSMIT	MODULATION	Transmitter State
Inactive	N/A	N/A	Off
Any value except inactive	Off	N/A	Off
	On	False	On, radiated output is carrier only
	On	True	On, data modulated onto the radiated carrier

Any value, except inactive, triggers the Transmit parameters to On or Off.
When TRANSMIT is *On* and MODULATION is *True*, the Physical Layer receives coded symbols for transmission from the Data Link Layer (C&S Sublayer), following FIFO (First-In-First-Out) rules. The data includes PLTUs and Idle data.

3.3. Receiver

The Physical Layer has three operational states from the receiving side that influence the receiver state, as shown in Table 3.2.

Table 3.2 – Receiver control variables

MODE	DUPLEX	TRANSMIT	Receiver State
Inactive	N/A	N/A	Off
Any value except inactive	Full or Simplex Receive	N/A	On
	Simplex Transmit	N/A	Off
	Half	On	Off
	Half	Off	On

The Physical Layer notifies the Data Link Layer (MAC Sublayer) of the status of the received channel, using the signals CARRIER_ACQUIRED and SYMBOL_INLOCK_STATUS. The Physical Layer delivers the received coded symbol streams to the Data Link Layer (C&S Sublayer). The receiver sweeps the frequency channel to which it is assigned in order to acquire carrier lock at an assigned frequency channel. During this process, the receiver first attempts to lock to the carrier frequency.

The CARRIER_ACQUIRED signal notifies the MAC Sublayer that the receiver has acquired a carrier signal. The CARRIER_ACQUIRED signal is set to *True* when the receiver is locked to the received RF signal and *False* when not in lock.

The SYMBOL_INLOCK_STATUS signal notifies the MAC Sublayer that symbol synchronization has been acquired and the received serial symbol stream is being provided to the Data Link Layer. The SYMBOL_INLOCK_STATUS signal is set to *True* when the receiver is in symbol lock and *False* when the receiver is not in symbol lock. The receiver is considered to be in symbol lock when it is confident that its symbol detection processes are synchronized to the modulated symbol stream. When SYMBOL_INLOCK_STATUS is *True*, the Physical Layer delivers the received symbol stream to the C&S Sublayer. (*Source [3]*)

3.4. Controlled Communications Channel Properties

The Proximity-1 protocol recommended standards is intended for a proximity link space environment far from Earth. Therefore, the frequencies were selected in order not to cause interference to radio communication services allocated by the Radio regulations of the International Telecommunication Union (ITU). In this regard, precautions have to be taken to protect frequency bands allocated to Near Earth Space Research, Deep Space, and Space Research.

3.5. Ultra High Frequencies (UHF)

In the vast majority of communication systems, frequency plays an important role. The main reason is interference. A communication link is established upon a frequency channel, and due to fading and interference it might require one or more frequency channels. The Ultra High Frequencies are between 300 MHz and 3 GHz, with the wave length ranging from one meter to one-tenth of a meter. There are several applications for the UHF such as Television Broadcast and Land Mobile services. In order to avoid interference, in space communication systems close to Earth, the frequencies near 430 MHz cannot be used. The solution is to add other frequencies to enable the same protocol to be used in near Earth applications. Therefore, a strict compliance with the frequency allocations in the ITU Radio Regulations is mandatory.

The frequency range for the UHF Proximity-1 links consists of 60 MHz between 390 MHz and 450 MHz with a 30 MHz guard-band between forward and return frequency bands. The forward frequency band shall be from 435 to 450 MHz, while the return frequency band shall be from 390 to 405 MHz *(Source [3])*.

The forward and return frequency pairs that the transceivers use to establish physical link communications are the hailing channels, detailed in section 3.6.

3.6. Hailing Channel

Hailing is an activity used to establish a proximity link with a remote vehicle. Hailing requires the use of a hailing frequency pair (bidirectional). Either elements can initiate hailing. The process is done at a low data rate and therefore is a low bandwidth activity. Channel 1 has been selected to minimize the use of UHF bandwidth. Hailing is performed between transceivers that are pre-configured. However, if transceivers are compatibly configured, hailing can occur on an agreed-to channel. The first-generation transceivers are fixed frequency and use Channel 0 (forward frequency at 437,1 MHz and return frequency at 401,59 MHz).

For interoperability at UHF, the default hailing channel shall be Channel 1 configured for 435.6 MHz in the forward link and 404.4 MHz in the return link. If the proximity link radio equipment supports only a single channel (i.e., a single forward and return frequency pair), then the hailing channel shall be the same as the working channel. If the proximity link radio equipment supports multiple channels, then the hailing channel shall be different from the working channel. After link establishment through hailing is accomplished, transition to the working channel (if available) should be done as soon as possible.

The channels 1 to 3 (fixed single forward and return frequency pairs) are well defined for Proximity-1 operations, whereas for the following channel numbers there is a frequency range that is available. The following Table 3.3 details Proximity-1 channel assignments from 0 through 7.

Table 3.3 - Proximity-1 channel assignments from 0 through 7

Channel Number	**Forward Frequency [MHz]**	**Return Frequency [MHz]**
0	437.1	401.585625
1	435.6	404.4
2	439.2	397.5
3	444.6	393.9
4	Within 435 to 450	Within 390 to 405
5	Within 435 to 450	Within 390 to 405
6	Within 435 to 450	Within 390 to 405
7	Within 435 to 450	Within 390 to 405

In the case where there is a need for one or multiple return frequencies paired with one or multiple forward frequencies, the forward frequencies shall be selected from 435 to 450 MHz band in 20 kHz steps and the return frequencies shall be selected from 390 to 405 MHz in 20 kHz steps. These frequency pairs shall be distinct from the frequency pairs defined in Channels 0 through 7. The forward and return frequency components of Channels 8 through 15 are reserved for this purpose. (*Source [3]*)

3.7. Modulation and Polarization

The Pulse Code Modulation (PCM) data is Bi-Phase-L encoded (also known as Manchester code) and is modulated directly into the carrier. The residual carrier shall be provided with modulation index of 60º ±5%. The symmetry of PCM Bi-Phase-L waveforms shall be such that the mark-to-space ratio is between 0.98 and 1.02. For directly modulated Bi-Phase-L waveform, a symbol ‘1’ shall result in an advance of the phase of the radio frequency carrier at the beginning of the symbol interval, while a symbol ‘0’ shall result in a delay, as Figure 3.2 represents. (*Source [3]*)

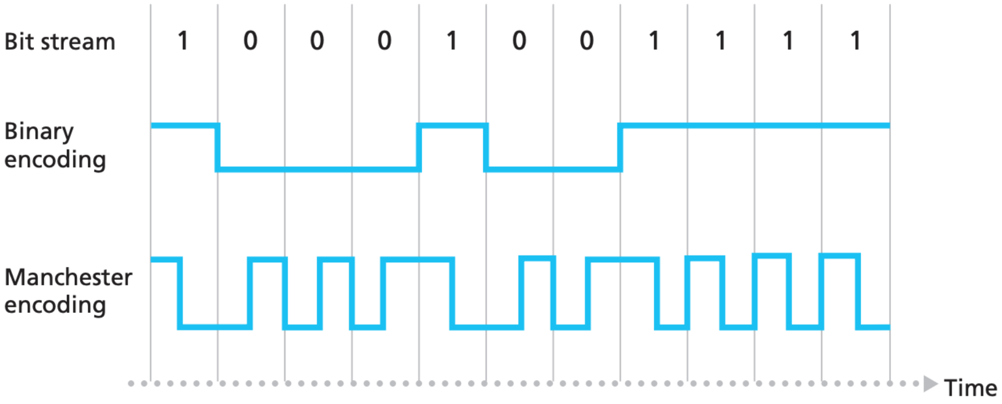


Figure 3.2 - Bi-Phase-L encoding *(source: [28] Stanford Computer Science Department)*

Regarding the Polarization, this protocol operates with Right Hand Circular Polarization (RHCP) for both forward and return links.

3.8. Proximity rates

According to the Proximity-1 Physical Layer recommended standard CCSDS 211.1-B-4, a communication link shall support one or more of the following 13 discrete forward and return values for the coded symbol rate R_{CS} shown in symbols per second: 1000, 2000, 4000, 8000, 16000, 32000, 64000, 128000, 256000, 512000, 1024000, 2048000, 4096000.

The correspondence between coded symbol rate (R_{CS}) and data rate (R_d) can be found in Annex A Table A.1.5. The data rate R_d is configured using the SET TRANSMITTER PARAMETERS, SET RECEIVER PARAMETERS and SET PL EXTENSIONS directives defined in Annex A; the coded symbol rate R_{CS} is set according to the set value of R_d and to the selected coding option. (*Source [3]*)

4. MATLAB Simulator

In order to have a better understanding of this complex protocol, a simulation of the Physical Layer and Data Link Layer was developed in MATLAB. This chapter describes the MATLAB simulator, detailing the two lowest layers of the OSI Model (Data Link and Physical Layers) according to the Proximity-1 protocol recommended standards.

It starts with an overview of the arquitecture of the simulator along with the communication and operations procedures as well as the time unit approach and implementation details. The following sections describe the implemented Physical Layer accompanied by the Data Link layer.

This chapter ends with a state diagram that allows a better understanding of the interactions between functions and the different states that are intrinsic to this simulation.

4.1. Simulator Architecture Overview

The simulator implemented in MATLAB recreates a communication link between two transceivers. Figure 4.1 and Figure 4.2 help visualize the architecture implemented.

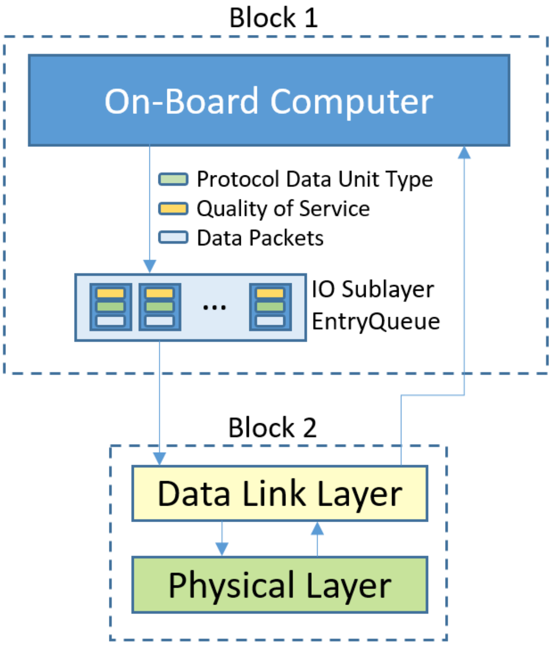


Figure 4.1 – Simulator Architecture focused in Block 1.

The simulator has two main blocks. The first block (represented by Block 1 in Figure 4.1) corresponds to the On Board Computer that loads data into buffers before entering the Data Link Layer. The second block corresponds to the Data Link Layer and Physical Layer processes between two transceivers.

The first block allows the On Board Computer to choose the Type of Protocol Data Unit (if it is a User Data-‘0’ or a Protocol Data-‘1’), also the Quality of Service required (Expedited frames-‘0’ or Sequence Controlled frames-‘1’), and finally the data packet. These three components are inserted in the first position of a cell array (acting as a buffer, more specifically a first-in-first-out queue). Additionally, the first value of this buffer is the input of the I/O Sublayer, therefore being called the IO Sublayer EntryQueue. Once the first block loads its data into the buffer, the processing begins on Block 2.[1]

The second block, represented in more detail in Figure 4.2, corresponds to the interoperability between the Data Link Layer and Physical Layer. This block includes two transceivers that are divided into two parts – a sending side and a receiving side – each side has its own variables. Inside the Data Link Layer, each sublayer side is an independent MATLAB function.

Furthermore, sublayers are interspersed by Queues, where information is written or removed. These waiting queues store the output of each sublayer. In addition, the following sublayer removes the first value of the queue, when available.

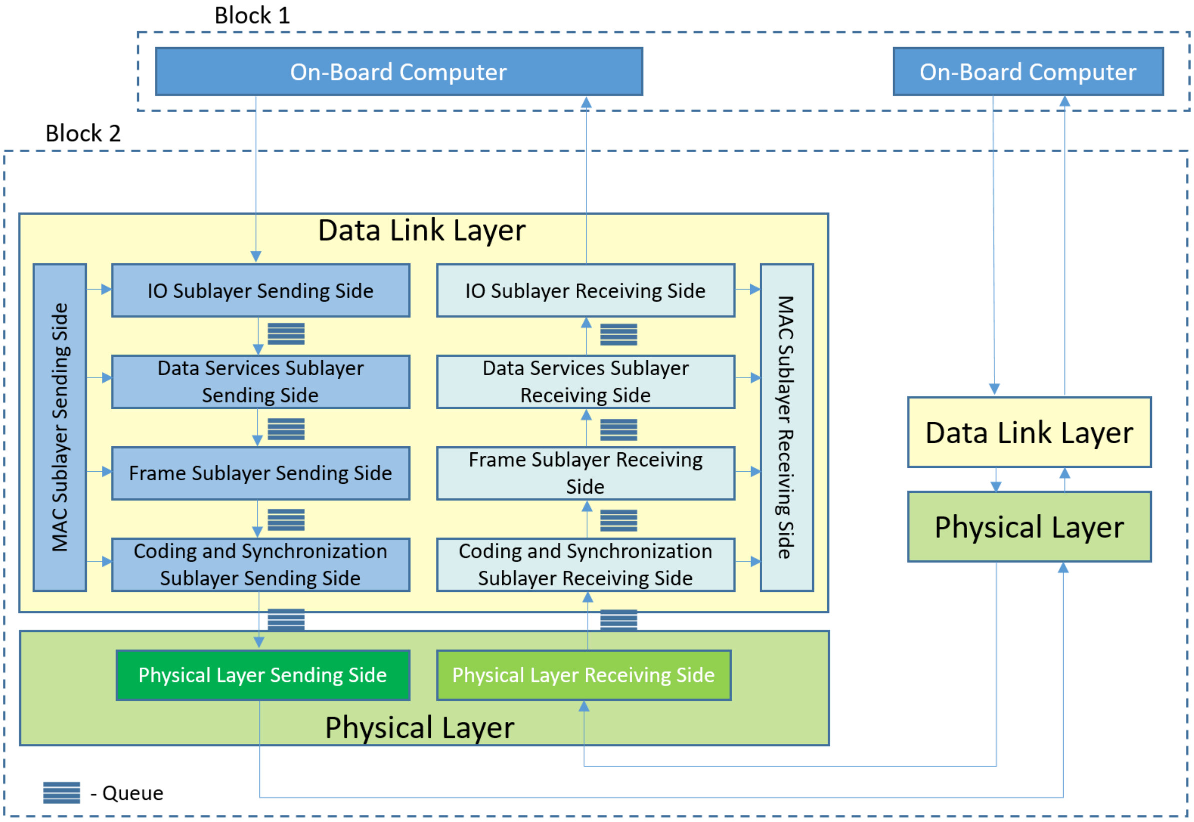


Figure 4.2 – Simulator Architecture focused in Block 2.[2]

The following sections describe complementary mechanisms and processes required for a good understanding of the simulator.

4.1.1. Frame Acceptance and Reporting Mechanism

The main cycle – Block 2 of the simulator - consists of data flowing from Transceiver A, into Transceiver B, then from Transceiver B back to Transceiver A. Figure 4.3 helps understanding this procedure.

---

[1] If there are more parameters to be configured, they might be added via MAC frames or directly into the I/O Sublayer when creating the frame header.

[2] Annex E contains a full picture of the implemented simulator.

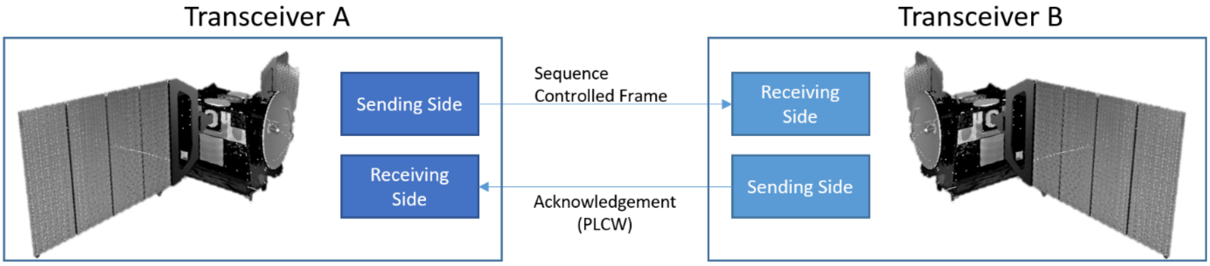


Figure 4.3 – Frame acceptance and reporting mechanism.

In case a frame has Expedited quality of service, the flow of data starts at Transceiver A sending side and arrives at Transceiver B receiving side, without requiring a response.

However, if the frame has a Sequence Controlled quality of service, the flow of data shall be the same as an Expedited quality of service frame, although, when arriving at Transceiver B, the quality of service requires an acknowledgement of the received frame. Therefore, Transceiver B, after receiving a Sequence Controlled frame, transmits a Proximity Link Control Word (PLCW) indicating the initial sender (Transceiver A) that the frame was received.

It might happen a frame arriving at Transceiver B with errors. In that case, the acknowledgement carries that information back to the sender requesting a retransmission of the corrupted frame.

This procedure informs the sending transceiver (A in this case) that a Sequence Controlled frame was received on Transceiver B, with or without errors.

4.1.2. Time Units

For the second block of the simulator, both Data Link Layer and Physical Layer must operate independently and asynchronously. In MATLAB, there is no function that allows multithreading. As such, the Physical and Data Link Layers operate with a Tic system, similar to a master clock that serves as a reference to each sublayer. All Sublayers have different processing times, hence, it is assigned a specific amount of Tics[1] (time unit) according to the complexity of each sublayer.

This system allows each sublayer to work independently. In fact, this solution allows having a multithreading system that MATLAB code does not grant.

In the simulation, there is a cycle incrementing the Tic values and checking if each sublayer is ready to output its value. Every cycle - when a Tic is incremented - the processing time of each sublayer is updated, and generates a message with the time remaining for each sublayer to output its value into a waiting queue. The single unit of time called Tic corresponds to the fastest processing time of a sublayer. From a 100 test experiment in real time, the assignment of Tics corresponds to the lowest time value for each sublayer performance.

Below, in Table 4.1, the processing times are assigned to each Sublayer, separated into Transceiver A and B, as well as sending side and receiving side. In Table 4.1 two use cases were considered. Transceiver A was transmitting a user-frame whereas Transceiver B was replying with a

---

[1] The Tic unit is well described in section 5.1.2 Processing Times.

supervisory protocol data unit, specifically a PLCW. This results in Transceiver A sending side having a higher processing time in comparison with the Transceiver B sending side.

User-frames are part of a PLTU, which can have up to 16440 bits, while a SPDU has a fixed length of 16 bits.[1] This justifies the different processing times regarding each transceiver.

Table 4.1 – Processing times of each transceiver.

Processing Time Unit [Tics]	**Transceiver A**		**Transceiver B**	
	Sending Side	**Receiving Side**	**Sending Side**	**Receiving Side**
Input-Output Subayer	3	4	3	4
Data Services Sublayer	2	3	1	3
Frame Sublayer	3	10	3	10
Coding and Synchronization Sublayer	10	1	10	1
Physical Layer	2000	1000	1650	1000

4.1.3. Implementation Details

This section describes some minor functions that are crucial for the proper functioning of each sublayer and for the simulator as a whole.

The first function worth highlighting is "*Clean*". This function is used to remove the first value of any buffer / FIFO queue after it is used in a specific sublayer or assigned to another variable inside the function sublayer. Thereafter, the queue is shifted one position, taking the position of the adjacent lower number. Then the last position of the queue is considered empty and a zero value is added to its place, to keep a fixed queue with 10 positions.

Additionally, a function is used to compare any two vectors. Specifically, the function "*PLTU_Compare*" matches the output of the Coding and Synchronization Sublayer sending side (which is a PLTU) with the received bit stream resulting from the output of the Physical Layer of the remote transceiver after transmission. This function works as an indicator to check if the frame was well received, for debugging issues. This parameter could not be used because the remote transceiver would not possibly know what was the original bit stream transmitted. It is only able to check if there were any errors during transmission.

For more complex timing services a function called *IsItReady* was created. Every sublayer function (sending and receiving sides both for Transceiver A and B) that requires processing time has

---

[1] There are also variable length SPDUs which can have up to 1200 bits and are used to transmit directives and status reports.

an *IsItReady* specific function. It receives the current time - measured in Tics, the time the sublayer takes to process its data, and the Sublayer function name. First, this function checks the actual time clock and adds the processing required time. Afterwards, it calculates when the sublayer will be ready to output its data. In order not to update the value each new Tic, this function must have “memory” to know how much time had passed since it was called.

This is possible due to persistent variables. These variables keep their last value after the function had come to an end. This way, it is possible to keep track by incrementing every advance of the Tic. When it reaches the processing time, the Sublayer function outputs its data. This concept applies to all Sublayers. Each has a different processing time and different internal counters (persistent variables) for “memorizing” the time left. For this reason, it is not enough to have only one *IsItReady* function and reuse it, but as many as the Sublayer functions in this simulation.

4.1.4. Variables

The implemented MATLAB simulation operates with different types of variables. At the very beginning, data is loaded from the On-Board-Computer to the I/O Sublayer in the form of cell arrays, represented in Figure 4.4. Each cell array position contains the data entered in the MATLAB command window. The first two values are *char* variables with one bit each and the third value is a string.

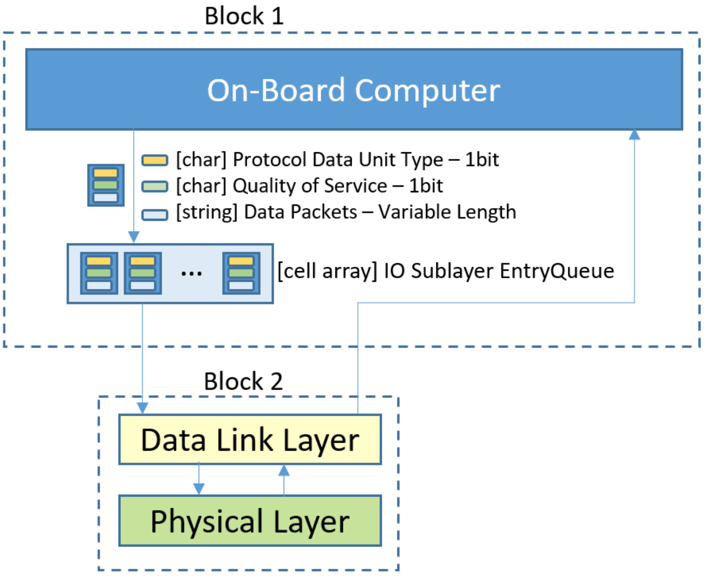


Figure 4.4 – Variables loaded from the On Board Computer.

Between each sublayer, there are waiting queues that are cell arrays with “memory” for ten allocations. This value is merely symbolic, since memory has limited space and this protocol needs to be optimized due to the environment where it will operate. Depending on the sublayers and their functions, data will have to be converted from *char* variables to base ten numeric variables to be incremented and converted back to binary base and finally to char variables or strings.

Each sublayer receives global variables that are changed within the function and need to remain visible to other functions. In addition to the global variables, each sublayer has a function (detailed in section 4.1.3) that indicates the processing time of the sublayer and the corresponding Tic, meaning, the moment when it will be ready to output the value into a waiting queue. This *IsItReady* function requires persistent variables; this type of variable keeps its value even when the function finishes its execution. If they were not persistent variables, it would constantly update the counter, without ever recording how much time had passed.

4.1.5. Text Files

In order to monitor the exchange of information between transceivers, and the processing times between sublayers, two *.txt* files were created.

The file named "Proximity_1.txt" contains the history of data each sublayer passed. Moreover, it contains the processing times at which every data of each sublayer is released to a queue. This file had the purpose of debugging in case of any unforeseen occurrence during any change in MATLAB code.

The other file created - named "Proximity_Summary.txt" - registers the exchanges of frames that occurred between transceivers chronologically ordered. In another words, this file contains the received frames in each transceiver and serves as a summary of frames that were successfully transmitted across the transmission channel.

4.2. Physical Layer Simulator

This section describes the Physical Layer Simulator, detailing the sending side as well as the receiving side. In addition, two algorithms were analyzed for the demodulation process.

4.2.1. Sending Side

The Physical Layer receives a bit stream provided by the Data Link Layer, more specifically, by the Coding and Synchronization Sublayer. This bit stream is converted into squared pulses, and then to polar data with Manchester Encoding, were the message is stored (Figure 4.5).

In the frequency domain, the Nyquist criterion states that the sampling frequency must be higher than twice the bandwidth in order to avoid aliasing ($f_s > 2B$). Whereas, in time domain the sampling rate (or sampling frequency) is the number of data samples acquired per second ($f_s = \frac{1}{\Delta t}$), where Δt is the amount of time between data samples. The smaller the Δt, the better the chance of measuring the correct wave form. If it is considered a transmission data rate of 2,048 Mbps, each bit period corresponds to 48,8 μs.

The simulations were performed with different values of samples per bit (detailed in sections 5.2 and 5.3). Moreover, each bit was represented by 3 carrier periods due to demodulation processes that are described in the receiving side.

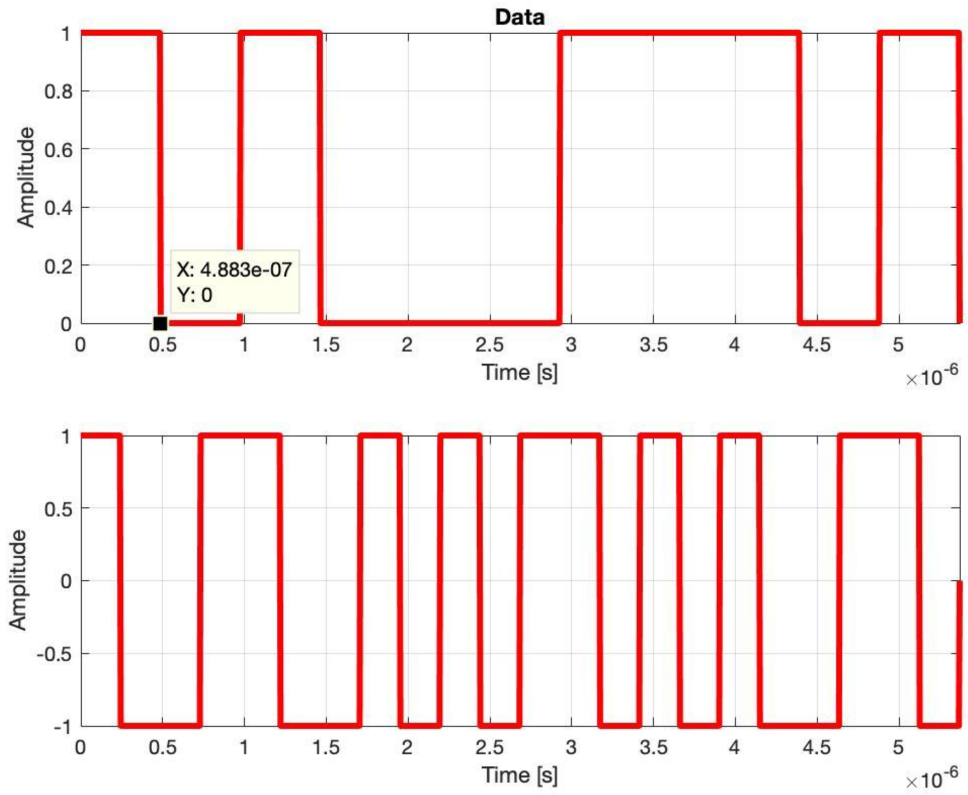


Figure 4.5 – Converting binary data into a Manchester encoding message

The modulated signal according to Proximity-1 protocol must be as follows:

$$mSig(t) = \sqrt{2P_t}\, sin(2\pi f_c t \; + \; \beta m(t) + \; \theta_c) \tag{4.1}$$

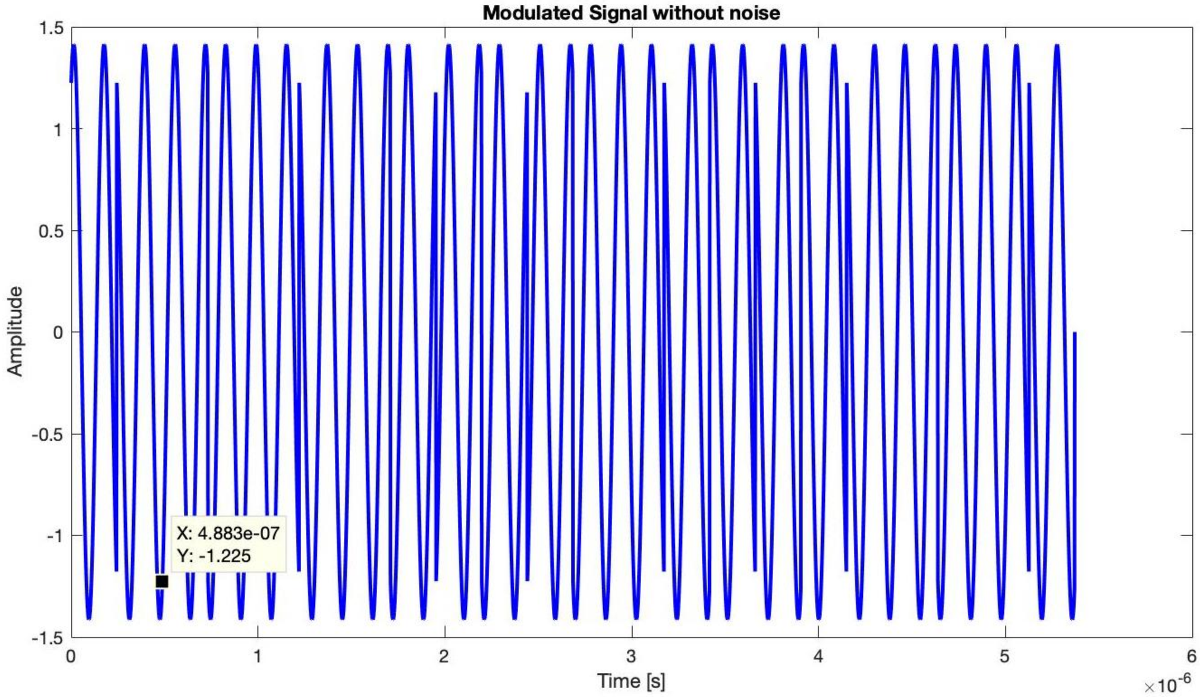


Figure 4. 6 - Modulated signal mSig(t)

The value β is the modulation index, that according to Proximity-1 protocol is $\frac{\pi}{3}$ (60º ±5%). P_t is the transmitted power (in Figure 4.6 P_t=1) and θ_c is the phase carrier. The Equation 4.1 can be rewritten as follows:

$$mSig(t) = \sqrt{2P_t}\sin(2\pi f_c \mathrm{t} + \beta \mathrm{m(t)} + \theta_c) \tag{4.1}$$

$$= \sqrt{2P_t}\left[\sin(2\pi f_c \mathrm{t} + \theta_c)\cos\left(\beta m(t)\right) + \cos(2\pi f_c \mathrm{t} + \theta_c)\sin\left(\beta \mathrm{m(t)}\right)\right] \tag{4.2}$$

$$= \sqrt{2P_t}[\cos(\beta)\sin(2\pi f_c \mathrm{t} + \theta_c) + \mathrm{m(t)}\sin(\beta)\cos(2\pi f_c \mathrm{t} + \theta_c)] \tag{4.3}$$

$$= \sqrt{2P_t\,(\cos\beta)^2}\sin(2\pi f_c \mathrm{t} + \theta_c) + \sqrt{2P_t\,(\sin\beta)^2}m(t)\cos(2\pi f_c t + \theta_c) \tag{4.4}$$

$$= \sqrt{2P_C}\sin(2\pi f_c \mathrm{t} + \theta_c) + \sqrt{2P_D}m(t)\cos(2\pi f_c t + \theta_c) \tag{4.5}$$

From the Equation 4.5 there are two signal components, a residual carrier ($\sqrt{2P_C}\sin(2\pi f_c \mathrm{t} + \theta_c)$) and a message carrier ($\sqrt{2P_D}m(t)\cos(2\pi f_c \mathrm{t} + \theta_c)$). This simplification is very useful for extracting the frequency and phase of the received signal. Another simplification considered from Equation 4.4 to 4.5 is the following: $P_C = P_t\,(\cos\beta)^2$ and $P_D = P_t\,(\sin\beta)^2$.

To simulate any possible Doppler effect, which implies a deviation in frequency and phase, the modulated signal passes through a channel with additive white Gaussian noise.

4.2.2. Receiving Side

From the receiving side, the demodulation process begins by filtering the received signal with a bandpass filter. The filter is centered at frequency f_c, which was obtained by applying a Fast Fourier Transform to the received signal and finding its maximum value. The error extracting the residual carrier is proportional to the width of the bandpass filter. The narrower the better, although, if the filter is too narrow, the magnitude of the signal might decrease significantly, due to the smooth cutoff frequency. Figure 4.7, represents a Fast Fourier Transform of the received modulated signal, centered at frequency 435.6 MHz, unfiltered and after applying a Bandpass filter, respectively. 435.6 MHz is the recommended standard frequency for channel 1 as the hailing channel for forward link establishment, see page 3-16 of reference [1].

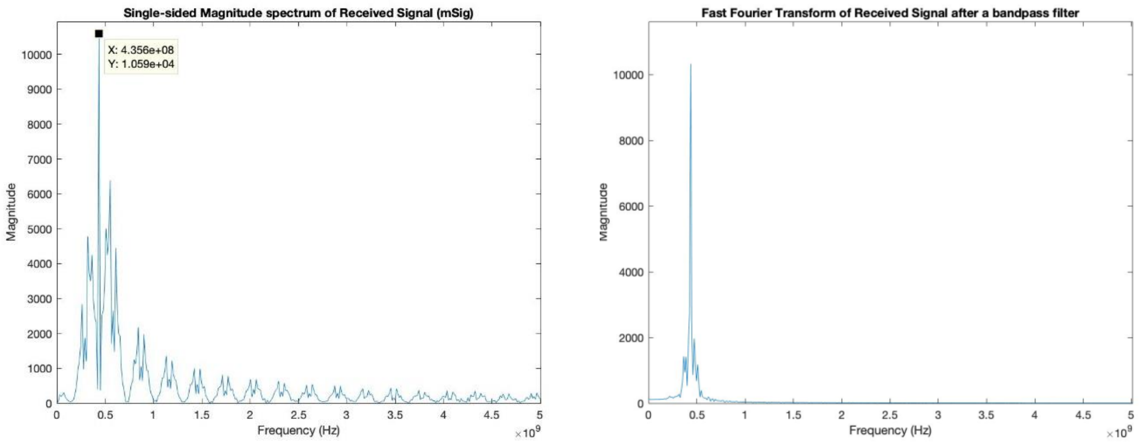


Figure 4.7 – Modulated received signal fast Fourier transform before *(left)* and after *(right)* a bandpass filter.

Once the frequency is obtained, the next step is finding the phase. Thus, a comparison is made between a signal with phase zero and the received signal, both with the same frequency. Hence, the frequency and phase of the received signal are now known.

In addition, an artificial cosine is generated with the same frequency and phase as the residual carrier, and it is multiplied by the received signal. The result passes through a Low Pass filter, where the output is the message demodulated.

In order to recover the data from the recently demodulated signal, a technique called integrate and dumping is used. Figure 4.8 represents the demodulated signal. It is not a perfect squared signal due to Bandpass and Lowpass filters characteristics. Comparing to Figure 4.5, the demodulated signal is similar to the original message.

$$Received\ Signal = \sqrt{2P_t\,(\cos\beta)^2}\sin(2\pi f_c \mathrm{t} + \theta_c) + \sqrt{2P_t\,(\sin\beta)^2}m(t)\cos(2\pi f_c t + \theta_c) \qquad (4.4)$$

$$Residual\ Carrier = \sqrt{2P_C}\sin(2\pi f_c \mathrm{t} + \theta_c) \qquad (4.6)$$

The artificial sine wave must be a cosine, otherwise the message would be eliminated after the Low Pass Filter. The following Equations demonstrate how the message is demodulated.
Multiplying the artificial cosine by the received signal, the following equations are obtained:

$$\left[\sqrt{2P_t\,(\cos\beta)^2}\sin(2\pi f_c \mathrm{t} + \theta_c) + \sqrt{2P_t\,(\sin\beta)^2}m(t)\cos(2\pi f_c t + \theta_c)\right] \times \mathrm{A}_0\cos(2\pi f_c t + \theta_c) \quad (4.7)$$

$$= \frac{\mathrm{A}_0\sqrt{2P_t\,(\cos\beta)^2}}{2}[\sin(2\pi(f_c + f_c)\mathrm{t} + \theta_c + \theta_c) + \sin(2\pi(f_c - f_c)\mathrm{t} + \theta_c - \theta_c)] +$$

$$+ \frac{\mathrm{A}_0\sqrt{2P_t\,(\sin\beta)^2}m(t)}{2}[\cos(2\pi(f_c + f_c)\mathrm{t} + \theta_c + \theta_c) + \cos(2\pi(f_c - f_c)\mathrm{t} + \theta_c - \theta_c)] \quad (4.8)$$

$$= \frac{\mathrm{A}_0\sqrt{2P_t\,(\cos\beta)^2}}{2}[\sin(2\pi(2f_c)\mathrm{t} + 2\theta_c)] + \frac{\mathrm{A}_0\sqrt{2P_t\,(\sin\beta)^2}m(t)}{2}[\cos(2\pi(2f_c)\mathrm{t} + 2\theta_c) + 1] \quad (4.9)$$

After the Low Pass Filter the residual carrier is filtered:

$$\frac{\mathrm{A}_0\sqrt{2P_t\,(\sin\beta)^2}m(t)}{2} \qquad (4.10)$$

Equation 4.10 is represented on Figure 4.8, considering $\mathrm{A}_0 = 1$, $P_t = 1$ and $\beta = \frac{\pi}{3}$, which results in $0.6\ m(t)$, approximately. Depending on the amplitude of the artificial cosine - A_0 - and the transmission power - P_t - the message might be closer to the original sent message.

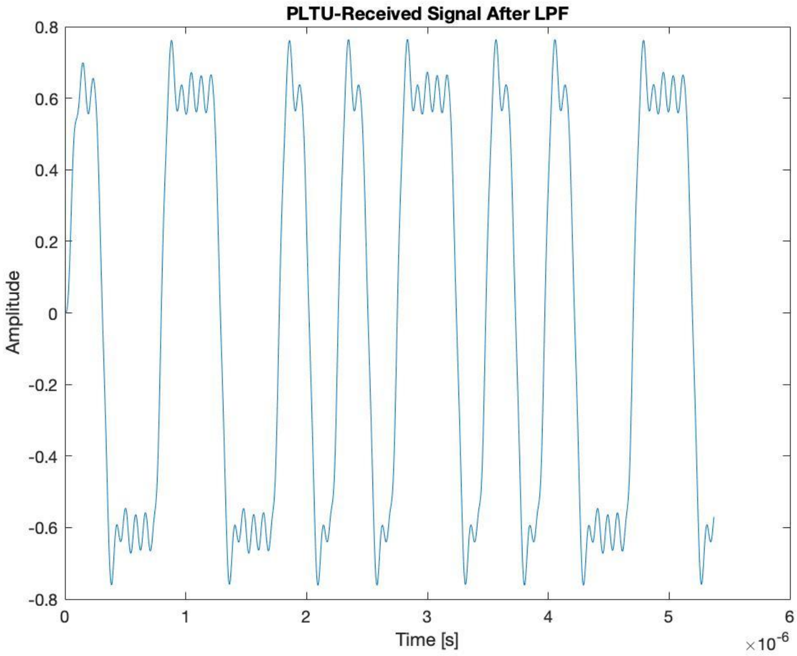


Figure 4.8 – Demodulated signal.

Figure 4.9 represents the simplified block diagram used to demodulate the received signal.

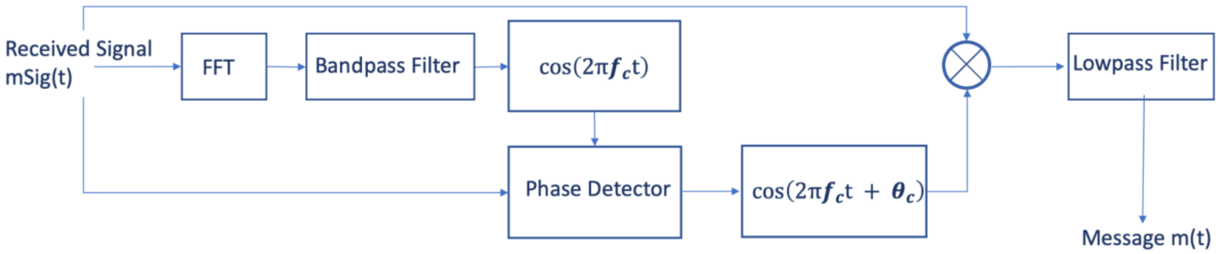


Figure 4.9 – Block diagram used to demodulate the Received Signal.

There are algorithms that can track the frequency and phase of a signal, such as Costas Loops and Phase Locked Loops, that are simulated in this dissertation.

4.2.3. Costas Loop

Costas Loop is a feedback algorithm for demodulation that synchronizes the carrier frequency and phase. Feedback carrier recovery techniques have a high noise rejection property but suffer from long loop settling times. However, Costas loop instantaneously feeds back the basebands signals I(t) and Q(t) to a phase detector which produces an error signal that drives the VCO. Furthermore, there is no detection delay in the loop. Moreover, the Costas loop can recover the carrier and demodulate the received signal simultaneously. This makes it highly computationally efficient. The operating principle of

Costas loop carrier recovery is “to iterate its internally generated carrier, the VCO, into the correct phase and frequency based on the principle of coherency and orthogonality (reference [11]).

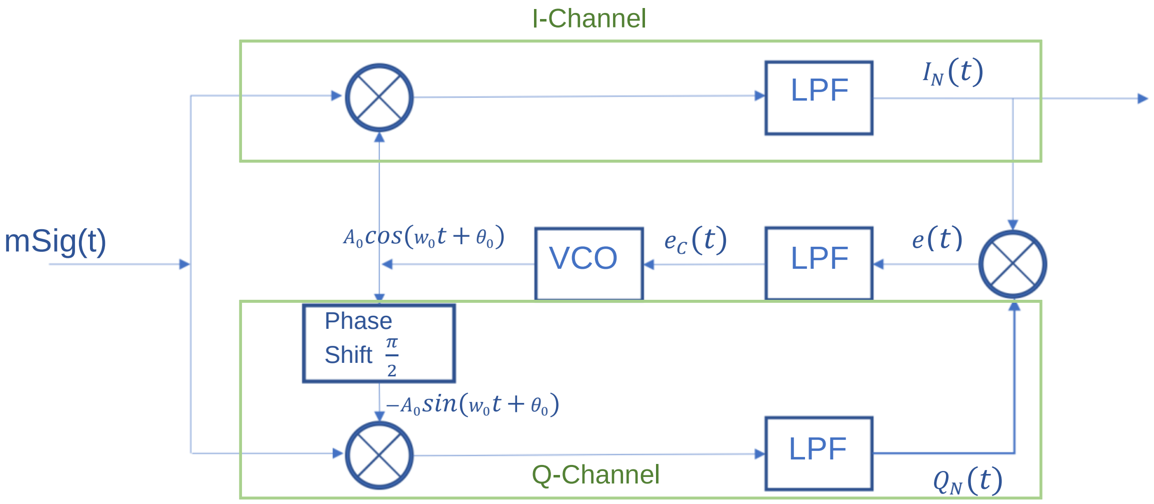


Figure 4.10 – Costas loop block diagram.

According to the Costas Loop Block Diagram, the received modulated signal mSig(t), represented in Equation 4.5, is multiplied in the upper arm (I-Channel) by an initial VCO output:

$$\left[\sqrt{2P_t\,(\cos\beta)^2}\,\sin(2\pi f_c t\;+\;\theta_c)+\sqrt{2P_t\,(\sin\beta)^2}m(t)\cos(2\pi f_c t\;+\;\theta_c)\right]\times\;A_0\cos(2\pi f_0 t\;+\;\theta_0)\tag{4.11}$$

$$=\frac{A_0\sqrt{2P_t\,(\cos\beta)^2}}{2}[\sin(2\pi(f_c+f_0)t\;+\;\theta_c+\theta_0)+\sin(2\pi(f_c-f_0)t\;+\;\theta_c-\theta_0)]+$$

$$+\;\frac{A_0\sqrt{2P_t\,(\sin\beta)^2}m(t)}{2}[\cos(2\pi(f_c+f_0)t\;+\;\theta_c+\theta_0)+\cos(2\pi(f_c-f_0)t\;+\;\theta_c-\theta_0)]\tag{4.12}$$

In the lower arm (Q-Channel) the received modulated signal is multiplied by the same VCO output with a 90º phase shift. Mathematically, it could be represented by the product of:

$$\left[\sqrt{2P_t\,(\cos\beta)^2}\,\sin(2\pi f_c t\;+\;\theta_c)+\sqrt{2P_t\,(\sin\beta)^2}m(t)\cos(2\pi f_c t\;+\;\theta_c)\right]\times(-A_0\sin(2\pi f_0 t\;+\;\theta_0))\tag{4.13}$$

$$=\frac{A_0\sqrt{2P_t\,(\cos\beta)^2}}{2}[\cos(2\pi(f_c-f_0)t\;+\;\theta_c-\theta_0)-\cos(2\pi(f_c+f_0)t\;+\;\theta_c+\theta_0)]+$$

$$+\;\frac{A_0\sqrt{2P_t\,(\sin\beta)^2}m(t)}{2}[\sin(2\pi(f_c+f_0)t\;+\;\theta_c+\theta_0)+\sin(2\pi(f_c-f_0)t\;+\;\theta_c-\theta_0)]\tag{4.14}$$

Subsequently, both outputs are passed into a Low pass filter, which removes the doubled frequency terms.

$$I_N(t) = \frac{A_0\sqrt{2P_t\,(\cos\frac{\pi}{3})^2}}{2}\sin(2\pi(f_c - f_0)\mathrm{t} \,+\, \theta_c - \theta_0)$$

$$+\;\frac{\mathrm{A}_0\sqrt{2P_t\,(\sin\frac{\pi}{3})^2 m(t)}}{2}\cos(2\pi(f_c - f_0)t \,+\, \theta_c - \theta_0) \qquad (4.15)$$

$$Q_N(t) = \frac{A_0\sqrt{2P_t\,(\cos\frac{\pi}{3})^2}}{2}\cos(2\pi(f_c - f_0)\mathrm{t} \,+\, \theta_c - \theta_0)$$

$$+\;\frac{\mathrm{A}_0\sqrt{2P_t\,(\sin\frac{\pi}{3})^2 m(t)}}{2}\mathrm{sen}(2\pi(f_c - f_0)t \,+\, \theta_c - \theta_0) \qquad (4.16)$$

A multiplication of $I_N(t)$ with $Q_N(t)$ follows, resulting in signal e(t). This signal is filtered by a Low Pass filter, where the output is a DC value. This value will be the input of VCO. Depending on this DC error value, the VCO adjusts its frequency and phase output.

The DC error belongs to an interval between [-1,1].

If the error is 0, VCO frequency output (f_0) matches the carrier frequency (f_C). If the error is 1, the VCO frequency output corresponds to $(f_0 = 2f_C)$. When the error is '-1', the VCO frequency output is '0'.

Once the frequency of the VCO output matches the carrier frequency, as well as its phase, the upper arm (I-Channel) sends the demodulated message to the upper layer (Data Link Layer, more specifically the Coding and Synchronization Sublayer).

To sum up, the objective of the Costas Loop is to maximize the energy in the I arm (in-phase) and minimize the energy in the Q-arm (quadrature-phase). Although the received signal has a residual carrier attached to the message carrier, the Costas Loop will only work correctly if there is no residual carrier. So, according to Proximity-1 protocol, before applying the Costas Loop algorithm, one must eliminate the residual carrier. One way of removing the residual carrier is described on section 4.1. After all, the Costas Loop algorithm requires some complex operations and there are processes of demodulating that are more effective and efficient than eliminating the residual carrier and applying the Costas Loop. That is why the approach chosen in this simulation is the demodulation process detailed in the previous section.

4.2.4. Phase Locked Loop

A Phase Locked Loop (PLL) is a tracking circuit that synchronizes an output signal generated by an oscillator, to the input frequency and phase references. This process is a closed loop feedback system combining a Phase Detector, a Low Pass Filter and a Voltage Controlled Oscillator (VCO). In Figure 4.11 is represented a diagram of a PLL.

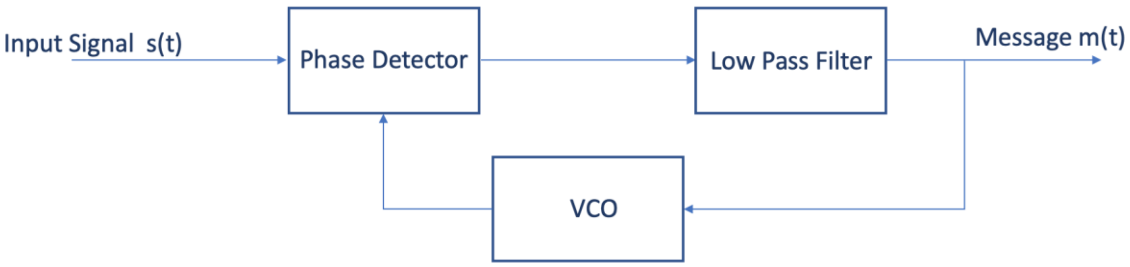


Figure 4.11 – Phase locked loop block diagram.

The VCO generates a periodic signal, whose angular frequency is determined by the output of the loop filter. The phase detector compares the phase of this output signal with the phase of the input signal, generating an output proportional to the phase error. The output from the Phase Detector has a DC and an AC component (which is removed by the Low Pass Filter). If a mismatch in phase occurs, the system tries to reduce it to a minimum. A PLL can either track the input frequency, or generate a frequency that is a multiple of the input frequency. The PLL system uses only three blocks.

The first block is a phase detector or a phase frequency detector. The phase detector generates an error signal proportional to the phase difference between its two inputs – one being the input signal and the other the feedback signal generated by the VCO.

The second block is the Low Pass Filter. It is responsible for specifying the bandwidth, so that it eliminates the unwanted higher frequencies. This filter converts these signals into a control voltage that is used to bias the VCO. Based on the control voltage, the VCO oscillates at a higher or lower frequency, which affects the phase and frequency of the feedback signal.

The third block is a positive feedback amplifier called the voltage controlled oscillator (VCO). The output of the VCO is simultaneously a square wave and a triangular wave outputs and it keeps changing with the input control voltage until the two frequencies are the same. The VCO oscillates at its own frequency (free running frequency), until an input is applied. The output of the low pass filter is a changing voltage that forces the VCO to respond quickly to reduce the frequency difference between the VCO output and the input signal. The PLL is in Locked state when the two frequencies become equal.

According to Proximity-1 protocol the received signal is:

$$s(t) = \sqrt{2P_t\,(\cos\beta)^2}\,\sin(2\pi f_c \mathrm{t} + \theta_c) + \sqrt{2P_t\,(\sin\beta)^2} m(t)\cos(2\pi f_c t + \theta_c) \qquad (4.17)$$

Which is multiplied by:

$$\mathrm{A}_0\cos(2\pi f_0 t + \theta_0) \qquad (4.18)$$

The result is the output of the Phase Detector represented in 4.19:

$$\frac{A_0\sqrt{2P_t\,(\cos\frac{\pi}{3})^2}}{2}\sin(2\pi(f_c+f_0)\mathrm{t}\ +\ \theta_c+\theta_0)+\frac{A_0\sqrt{2P_t\,(\cos\frac{\pi}{3})^2}}{2}\sin(2\pi(f_c-f_0)\mathrm{t}\ +\ \theta_c-\theta_0)+$$
$$+\ \frac{\mathrm{A}_0\sqrt{2P_t\,(\sin\frac{\pi}{3})^2 m(t)}}{2}\cos(2\pi(f_c+f_0)t\ +\ \theta_c+\theta_0)$$
$$+\ \frac{\mathrm{A}_0\sqrt{2P_t\,(\sin\frac{\pi}{3})^2 m(t)}}{2}\cos(2\pi(f_c-f_0)t\ +\ \theta_c-\theta_0) \qquad (4.19)$$

The output of the Phase Detector represented in Equation 4.19 is then passed into a Low Pass Filter. The output of this LPF is represented in Equation 4.20 where the higher frequencies are eliminated.

$$\frac{A_0\sqrt{2P_t\,(\cos\frac{\pi}{3})^2}}{2}\sin(2\pi(f_c-f_0)\mathrm{t}\ +\ \theta_c-\theta_0)$$
$$+\ \frac{\mathrm{A}_0\sqrt{2P_t\,(\sin\frac{\pi}{3})^2 m(t)}}{2}\cos(2\pi(f_c-f_0)t\ +\ \theta_c-\theta_0) \qquad (4.20)$$

When $f_c = f_0\ and\ \theta_c = \theta_0$, the final result will be $\frac{\mathrm{A}_0\sqrt{2P_t\,(\sin\frac{\pi}{3})^2}}{2}m(t)$. This means the final message will be modulated in amplitude. For more details see references [9] and [10].

The Phase Locked Loop was not ideal for the protocol Proximity-1 as it requires some iterations in order to find the exact frequency and phase. This way, the best solution to demodulate the signal was the first option described in section 4.2.2.

4.3. Data Link Layer Simulator

In this section, the sublayers' interoperability is described, as well as the procedures it encompasses. The Data Link Layer processes all the data across all sublayers between the On-Board Computer and the Physical Layer.

Considering that each sublayer has a sending side and a receiving side, there is a separate function for each side. Although they are different functions, a sublayer is the combination of both sending and receiving sides.

4.3.1. Sending Side

In this section, the implementation of each sublayer is described taking into account the operations, procedures and the interoperability between them. All the processes implemented comply with the Proximity-1 protocol recommended standards.

IO Sublayer Sending Side

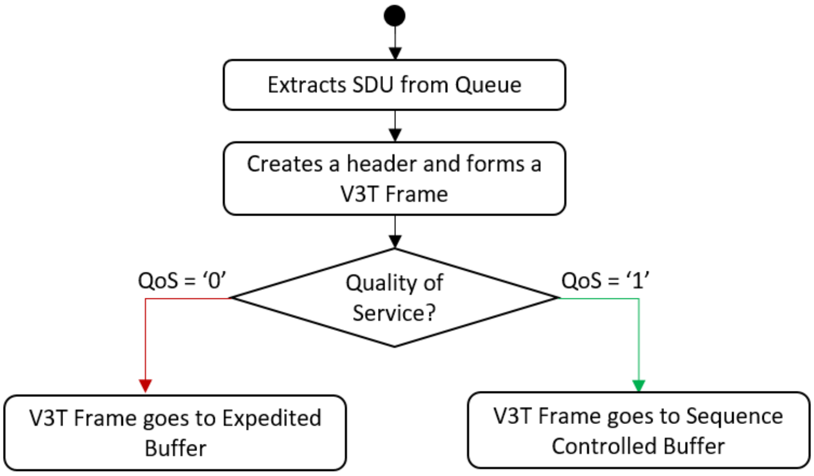


Figure 4.12 – IO Sublayer sending side.

The I/O Sublayer sending side, implemented in function "*IOSublayer_Tx_A"*, represented by Figure 4.12, extracts the first value of the "*IOSublayer_Entry_Queue",* which is a first-in first-out (FIFO) buffer where the On-Board Computer outputs service data units (SDUs).

After the extraction, the length of a SDU is verified and in case the length is bigger than 16344 bits (for simulation purposes 16 bits have been considered) it subdivides it into smaller data units. Then, a Version-3 Transfer Frame is created with a specified header. The header characterizes the data with important information, which impacts the data flow of this frame, such as the quality of service the spacecraft Identification and type of data, among others.

Subsequently, the version-3 transfer frame is placed in different buffers, according to its quality of service, in the Expedited Buffer or in the Sequence Controlled Buffer.

Data Services Sublayer Sending Side

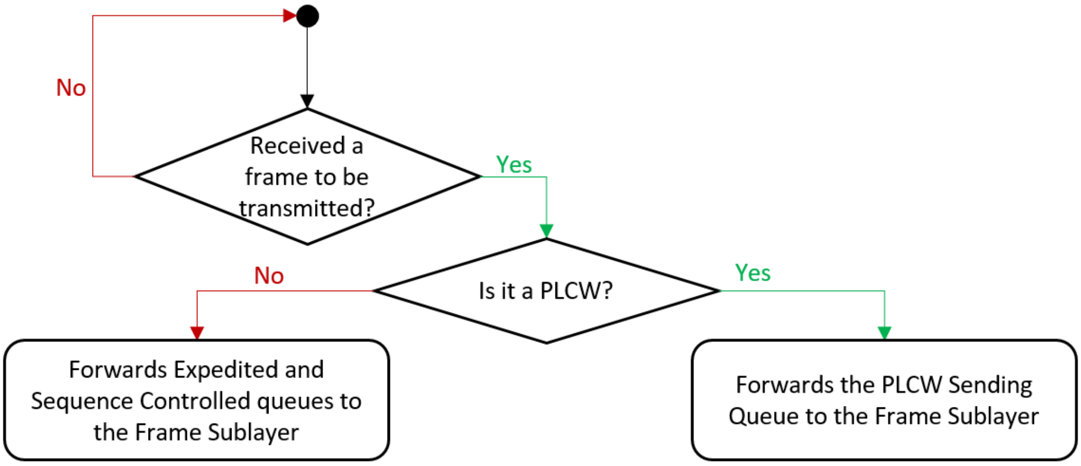


Figure 4.13 – Data Services Sublayer sending side.

The Data Services Sublayer sending side is implemented in function *DATAServicesSublayer_Tx_A* and simply forwards both buffers from the I/O Sublayer to the adjacent Frame Sublayer. As the Data Services Sublayer is responsible for the FARM process, in case a Sequence controlled frame has been received, it forwards the PLCW queue to the Frame Sublayer with the recently created PLCW in the Data Services Receiving side. These procedures can be viewed in Figure 4.13.

Frame Sublayer Sending Side

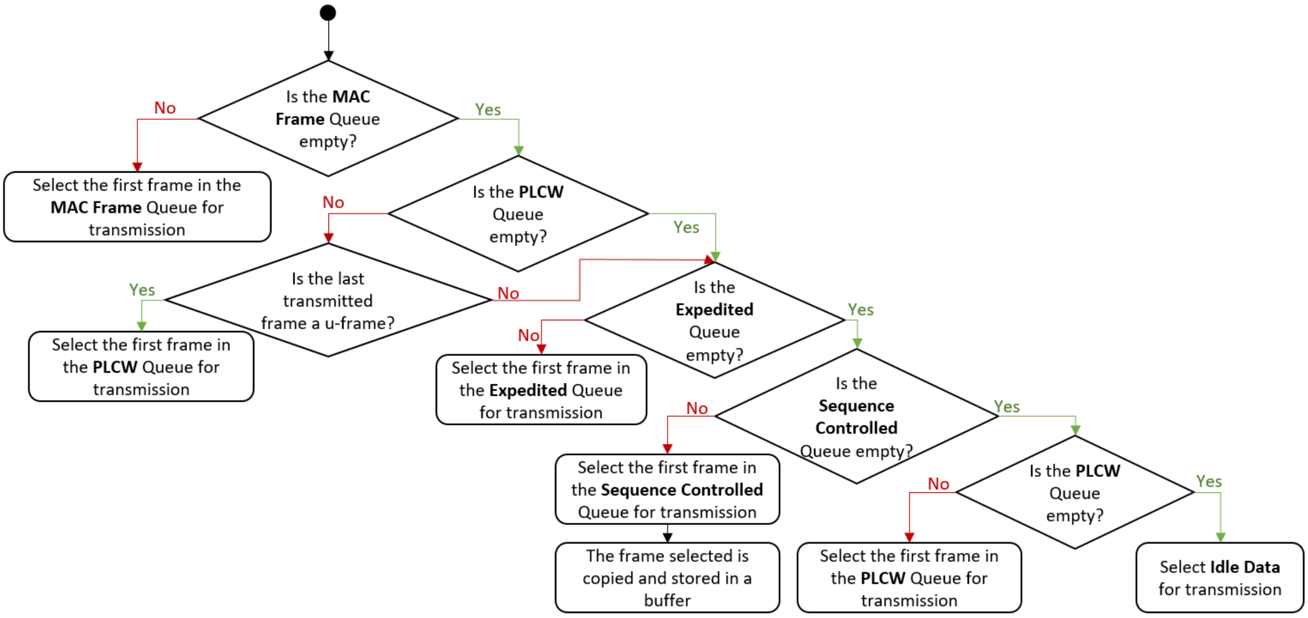


Figure 4.14 – Frame Sublayer sending side.

The *FRAMESublayer_Tx_A* is the function for the sending side of the Frame Sublayer. This function, receives the first value of each queue (Expedited buffer, Sequence Controlled buffer, PLCW buffer and MAC buffer) and selects a frame according to a well defined priority list:

1st .MAC Frame;
2nd .FARM Frame (PLCW), if the last transmitted frame was a User frame;
3rd .Expedited Frame;
4th .Sequence Controlled Frame;
5th .FARM frame (PLCW).

After the frame is selected, it is inserted in the Coding and Synchronization Sublayer entry queue. These procedures can be viewed in Figure 4.14.

Coding and Synchronization Sublayer Sending Side

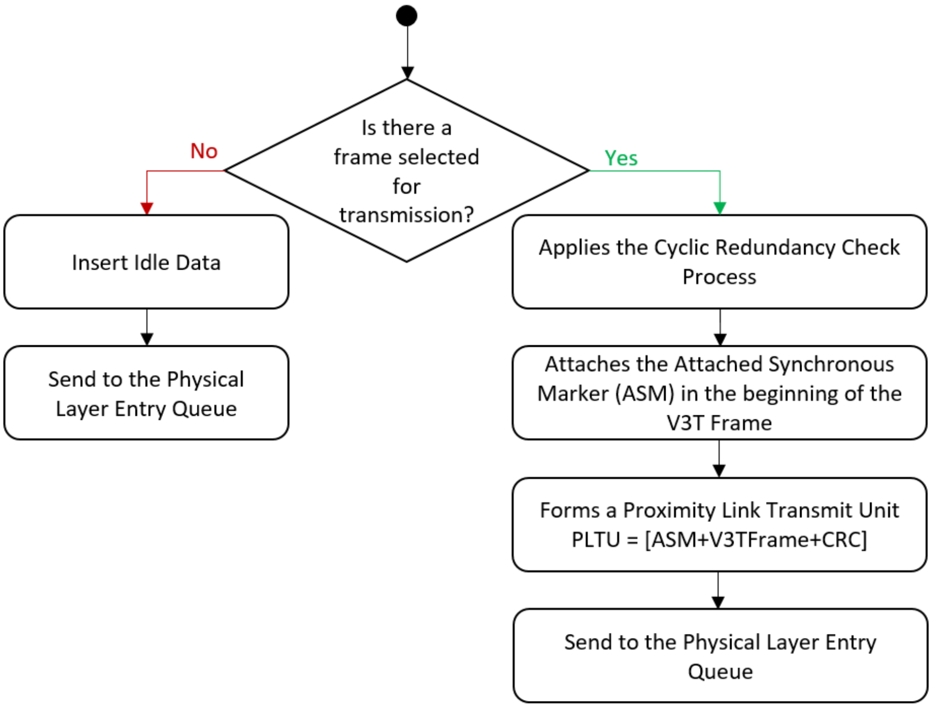


Figure 4.15 – Coding and Synchronization Sublayer sending side.

The Coding and Synchronization Sublayer sending side is implemented in function *CS_Sublayer_Tx_A*. This function receives the selected frame for transmission and applies the cyclic redundancy check operation. These procedures can be viewed in Figure 4.15.

For this procedure, both Transceivers (A and B) have a common polynomial that is used to divide the data frame. The remainder of the operation is the bit structure that is attached to the Transfer Frame. For more details regarding Cyclic Redundancy Check procedures, please see Annex B.

Besides the cyclic redundancy check bit structure, an attached synchronous marker (ASM)[1] is attached to the beginning of the frame. The frame – composed by an ASM followed by a Version-3 Transfer Frame and a CRC check attached at the end – is now called a Proximity Link Transfer Unit (PLTU).

In case the Frame Sublayer has not selected a frame for transmission, the Coding and Synchronization Sublayer inserts a serial bitstream into a PLTU called idle data[2].

Additionally, in this Sublayer, there is a serializer that converts the PLTU (which is a cell array composed by strings and vectors) into a single-bit-spaced-vector.

Before inserting the PLTU vector to the Physical Layer Entry Queue, a coding option is selected – Low Density Parity Check code, Convolutional code or bypasses all codes.

Finally, the PLTU vector is sent to a waiting queue to be transmitted by the Physical Layer.

---

[1] ASM is 'FAF320' in hexadecimal base or '1111 1010 1111 0011 0010 0000' in binary.

[2] The idle data is '352EF853' in hexadecimal base or '0011 0101 0010 1110 1111 1000 0101 0011' in binary.

Physical Layer Sending Side

On the sending side of Transceiver A, the Physical Layer modulates the received bitstream and sends the signal to Transceiver B. This process is well described in section 4.2 sending side.

4.3.2. Receiving Side

In this section, the implementation of each sublayer is described taking into account the operations, procedures and the interoperability between them. All the processes implemented comply with the Proximity-1 protocol recommended standards.

Physical Layer Receiving Side

On the receiving side of Transceiver B, a modulated signal is received in the Physical Layer that demodulates the received signal, converts into a bit stream and outputs the binary vector into a buffer before entering the Coding and Synchronization Sublayer. This process is well described in section 4.2 receiving side.

Coding and Synchronization Sublayer Receiving Side

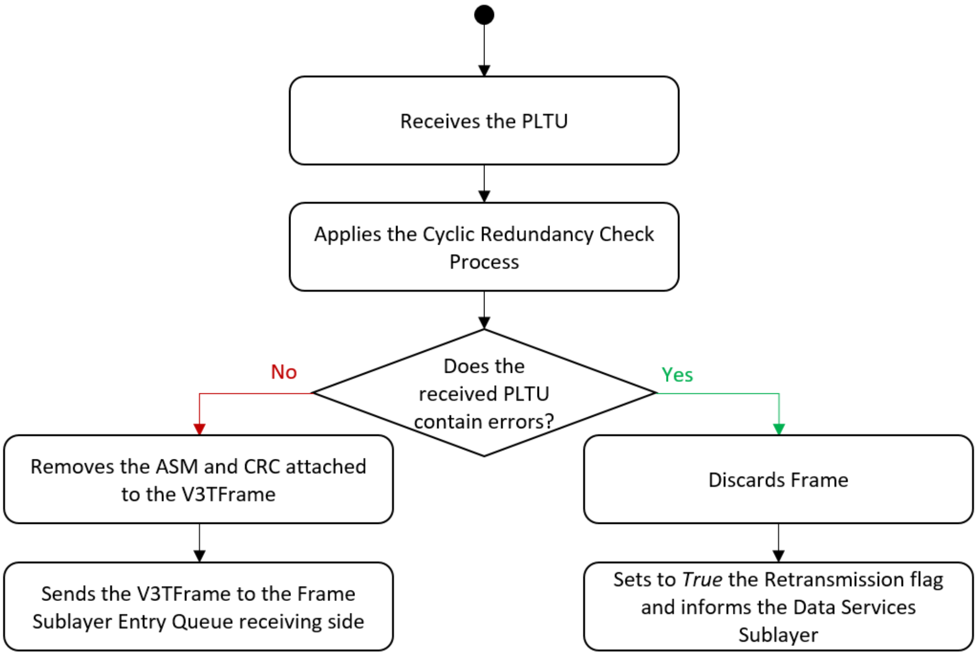


Figure 4.16 – Coding and Synchronization Sublayer receiving side.

The Coding and Synchronization Sublayer receiving side function - *CS_Sublayer_Rx_B* - receives the first position of a buffer, corresponding to the serial bit stream sent by the remote Transceiver A. Then, to make sure the PLTU was received without errors, the CRC is applied. Regarding the CRC process, the remainder of the division must be zero. Otherwise, an error occurred during transmission and the retransmission flag must be set to *True*. This flag informs the Data Services Sublayer to send an acknowledgement back to Transceiver A requesting the retransmission of the last Sequence Controlled frame sent. In case there are no errors, both the attachments (ASM and CRC) are removed and the Version-3 Transfer Frame is sent to a buffer to be read by the Frame Sublayer. These procedures can be viewed in Figure 4.16.

Frame Sublayer Receiving Side

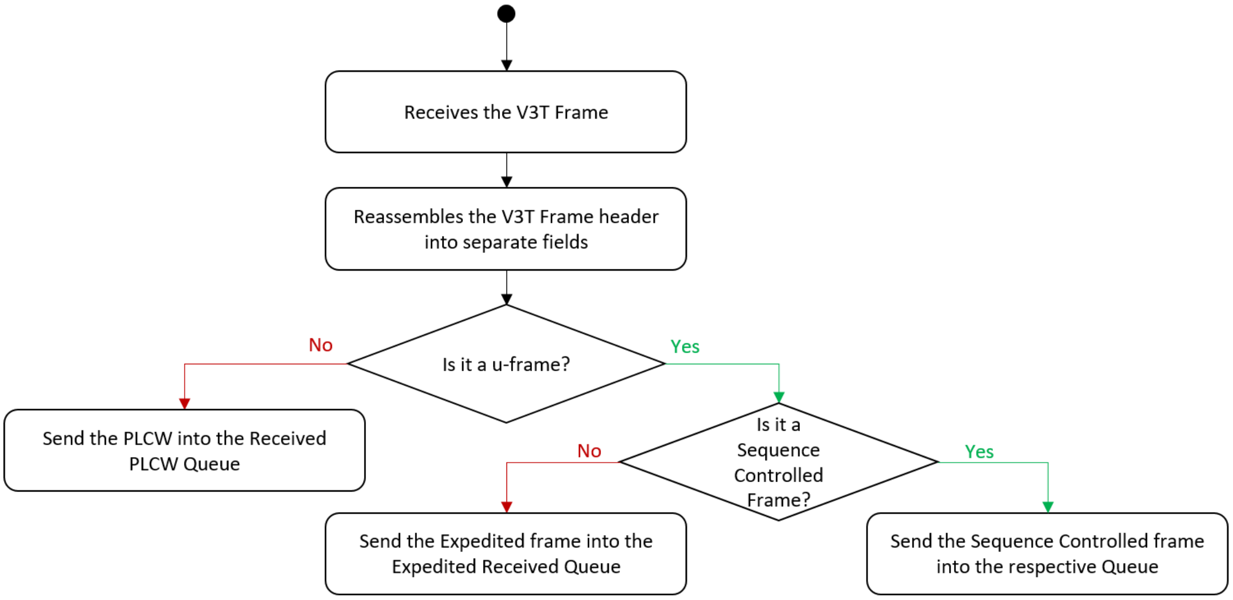


Figure 4.17 – Frame Sublayer receiving side.

The *FRAMESublayer_Rx_B* function extracts the Version-3 Transfer Frame from the Buffer and reassembles the V3T Frame header.

This sublayer also checks the data length to be coherent with the frame header section *Frame_Length*.

After the frame is organized, it goes either in the Expedited Buffer (*Expedited_Buffer_Rx_B*) or in the Sequence Controlled Buffer (*SeqControlled_Buffer_Rx_B*). In case the frame received is an acknowledge frame (Proximity Link Control Word) it goes to the Received PLCW Buffer (*PLCW_Receive_Queue_Rx_B*). These procedures can be viewed in Figure 4.17.

Data Services Sublayer Receiving Side

The receiving side from the Data Services Sublayer is implemented in function *DATAServicesSublayer_Rx_B*. This function analyzes the quality of service of the frame received and records the number of Expedited and Sequence Controlled frames received. In case the frame received has Sequence Controlled quality of service, a PLCW is created. The function updates the PLCW values – the number of expedited frames received and inserts the retransmission flag.

The retransmission flag will indicate whether the sender is required to send the last sequence controlled frame, or not. The PLCW structure is detailed in Annex C. These procedures can be viewed in Figure 4.18.

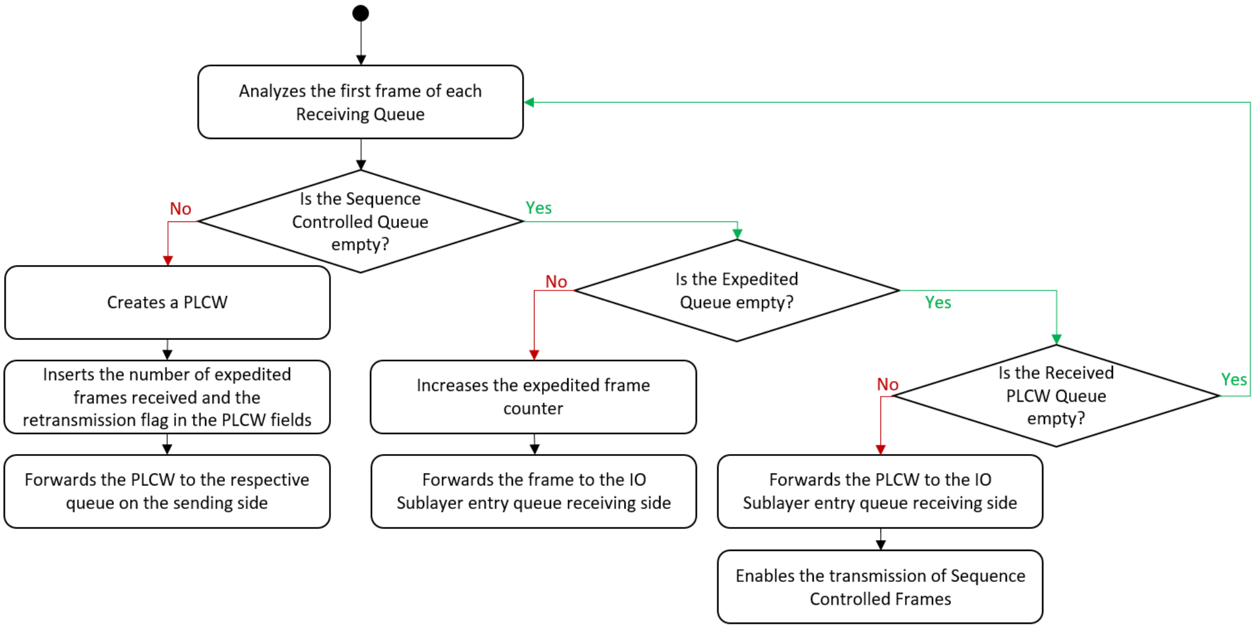


Figure 4.18 – Data Services Sublayer receiving side.

IO Sublayer Receiving Side

The last sublayer of the receiving side is the I/O Sublayer implemented in function *IOSublayer_Rx_B*. This sublayer receives the frames from each buffer (Sequence Controlled, Expedited or PLCW) and notifies the On-Board Computer. The OBC is represented by MATLAB input and output Command Window, and the received frame history is recorded in a .txt file. After the notification, the first value of the buffer is removed. These procedures can be viewed in Figure 4.19.

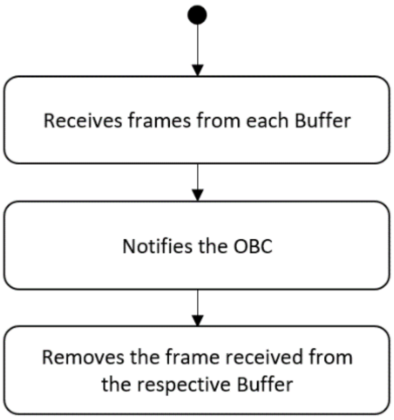


Figure 4.19 – IO Sublayer receiving side.

Note: The Mac Sublayer was not implemented as a function in the same way the other Sublayers were. The directives that the Mac Sublayer manages are modified manually on the MATLAB command window or directly in the simulation code. This way allows the programmer to insert the directive accordingly. This does not affect the data flow between sublayers and enables the simulation to comply with the protocol standards.

4.4. State Diagram

This section approaches a complementary view of the implemented simulation. With the help of a schematic overview (represented in Figure 4.20) this section allows for a better understanding of the interactions between functions and the different states that are intrinsic to this simulation. It is called a State Diagram.

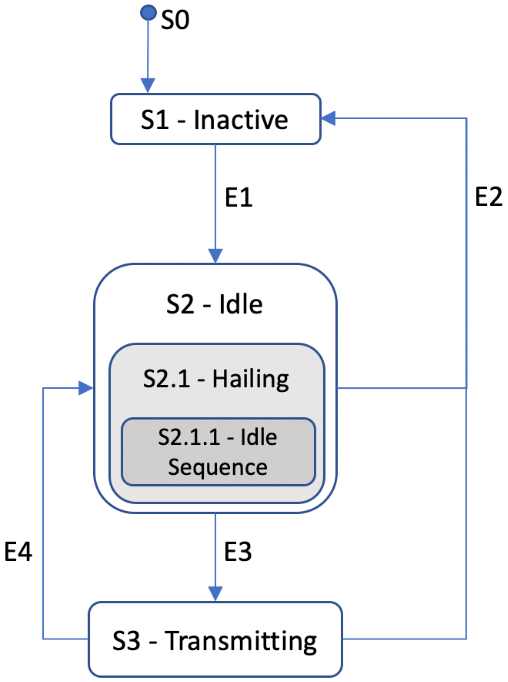


Figure 4.20 – Simulation state diagram send side.

Depending on the various stages of processing of each sublayer function, the communication session link between two remote transceivers has different states. From Transceiver B point of view the initial state is “inactive”, where no frame nor idle data is being transmitted.

When two transceivers (orbiter/rover/lander) are in the line of sight, the transmitter sends an acquisition signal to synchronize the frequency. This process is called hailing. At this stage the frequency is tuned and, in case there are frames to be sent, data transmission begins (entering the transmission state).

At the end of this data transmission period, the sender dispatches a set of pre-defined bits that indicates the end of the data transmission. This set of bits is called idle tail. Thus, the transceiver returns to idle / stand-by mode, in case there is another set of data frames ready to be sent. During the phase when both transceivers are in line of sight, they alternate the state between idle and transmission states, depending on whether there are data frames to be transmitted or not.

There are three operating modes for the communication session considered in the recommended standards Proximity-1 protocol: duplex, half-duplex and simplex. This simulation focusses on duplex mode, although it could easily incorporate half-duplex or simplex modes.

Regarding the full duplex and half-duplex modes, in this simulation the full duplex mode is implemented, as both transceivers work independently. The protocol contemplates a set of different frequencies for transmitting and receiving, in case there is a desire to send and receive frames simultaneously.

With different frequency channels, it is more efficient to have this continuous communication flow instead of interrupting it. If transceiver A is transmitting, while the transceiver B is limited to receiving only, it is not very efficient. Besides, in both transceivers there is a separation between the sending side and the receiving side, and they work independently. Nevertheless, there is interoperability between sublayers. This favors a full duplex mode in the communication link, where both transceivers can be transmitting and receiving at the same time.

In case there is the need to carry out the communication session in half-duplex mode, it is also possible. There is only a requirement to introduce one parameter in both transceivers that indicates whether you are receiving or sending frames, to avoid having both operations occurring simultaneously.

Table 4.2 – Event transition table.

Event	Description	Starting State	Next State
E1	Transceivers are in sight	S1	S2
E2	Transceivers are not in sight	S2	S1
E3	Frame ready to be transmitted	S2	S3
E4	No frame to be transmitted	S3	S2

Except for the Inactive state, the transceiver has the receive state always on, whether it is transmitting or in Idle state. This applies for full duplex mode, while for half duplex, when the transceiver is transmitting, it cannot be receiving, and vice-versa. This is represented in Table 4.2. Furthermore, Idle state S2 indicates the transceiver is ready to send Idle data, as well as to receive data. Concerning full duplex, the transceiver can execute both. Meanwhile, in half duplex, the transceiver in Idle state can only receive data before the hailing procedure. For this mode, the transceivers alternate between transmitting or receiving data.

Table 4.3 – State table

State	Description	Full Duplex		Half Duplex		Simplex[1]	
		Transmit	Receive	Transmit	Receive	Transmit	Receive
S1	Inactive	Off	Off	Off	Off	Off	Off
S2	Idle	On	On	Off	On	On/Off	Off/On
S2.1	Hailing	On	On	On	Off	On	Off
S2.1.1	Idle Sequence	On	On	On	Off	On	Off
S3	Transmitting	On	On	On	Off	On	Off

---

[1] For the simplex mode there is a parameter that indicates whether the transceiver is a transmitter or a receiver.

To better clarify the difference between half-duplex mode and simplex mode, consider that in simplex transmission mode the communication between the sender and the receiver occurs in only one direction. The sender can only send data, and the receiver can only receive data. The receiver cannot reply to the sender. Whereas in half-duplex mode, the communication between sender and receiver occurs in both directions, but only one at a time. The sender and receiver can both send and receive the information, but only one is allowed to send it at any given time.

5. Results and Discussion

This chapter covers several details of the implementation in MATLAB, which had to be considered to make the protocol compatible within its functions and capabilities — particularly data processing variables, how to improve the Communications Operations Procedures.

Furthermore, Chapter 5 considers different communication scenarios. It discusses ways of simulating different transceivers (orbiter, lander or rover) and the different environments between them, considering noise, atmosphere and fading. Thus, the signal-to-noise ratio will vary, as will the power of the signal emitted. Likewise, the type and order of the filters are changed, to analyze its effect on the received demodulated signal.

Finally, this section describes operational issues and presents future recommendations.

5.1. Processing Times

In this simulation, each unit of time, designated as a Tic, is approximately 0,2 milliseconds. This time was obtained experimentally using the MATLAB tic-toc integrated function. The time was measured once the sublayer function was called until the end of its processing. Every simulation was carried out in a similar test environment, that is, with the same conditions from the beginning until its completion.

The computer processor was used both for running the simulation in MATLAB and for other system tasks. Between each simulation the usage of the processor was minimized, in order to optimize it (eliminating tasks in the background, or others that could interfere with the performance of the simulation).

Therefore, of the one hundred experiments carried out, the time considered and allocated to each sublayer corresponds to the shortest time recorded and not the average of the collected times.

The main reason for this decision lies on the fact that, if each sublayer was able to execute the task in that reduced time, it means that in an ideal environment (where the protocol implementation has a dedicated processor) it would also execute it in that short amount of time.

The processor used in this experiment has an iOS operating system with 16GB ram memory processing capabilities, 2.7 GHz Intel Core i5 dual core. In order, not to limit the processing time conditioned by the processor (in the future, it might be upgraded), one considered the Tics as relative time units between sublayers, thus reflecting a comparative time period between processor-independent functions.

This way, it is intended to make the simulation as independent as possible from processing technologies, enhancing comparative studies between sublayers. Considering the processor model, if studies are to be carried out regarding an absolute-time experiment instead of a relative-time experiment, it is also possible using the Tic time unit (0.2 ms) as a reference.

Evidently, every sublayer will have its processing time depending on the degree of complexity of its operations. However, it would be expected that the functions that represent sublayers on Transceiver A would have the same processing time as those on Transceiver B. As can be seen in section 4.1.2, the functions have different times on the transmitting side between Transceiver A and B.

Ideally, they would have the same processing time, however, this is due to the fact that they have different purposes. Transceiver A transmits every type of frame, while Transceiver B transmits only PLCW frames – acknowledgements.

On the transmission side, the I/O Sublayer was not considered in the simulation, since it is programmed to send protocol frames (PLCW – acknowledgements) and not to receive information from the On-Board Computer.

The processing times between Transceiver A and B on the transmitter side are very similar, only varying in the Physical Layer and Data Services Sublayer, which the Transceiver B side has less processing time, as can be seen in the following Table (Table 4.1 from section 4.1.2).

Table 4.1 – Processing times of each transceiver.

Processing Time Unit [Tics]	**Transceiver A**		**Transceiver B**	
	Sending Side	**Receiving Side**	**Sending Side**	**Receiving Side**
Input-Output Subayer	3	4	3	4
Data Services Sublayer	2	3	1	3
Frame Sublayer	3	10	3	10
Coding and Synchronization Sublayer	10	1	10	1
Physical Layer	2000	1000	1650	1000

In the case of Data Services Sublayer, the differences are due to the fact that this sublayer, on the Transceiver B receiving side, accepts the Sequence Controlled frame buffer and the Expedited frame buffer, both empty, since the Transceiver B is programmed to emit PLCW, and does not receive data from the On-Board Computer.

Regarding the Physical Layer, the message to be sent by Transceiver B is shorter than a usual frame. A PLCW only has a length of 2 bytes compared to up to 2043 bytes in a Version-3 Transfer Frame, hence shortening the processing time on Transceiver B Physical Layer, compared to Transceiver A.

In other sublayers the procedure is similar, resulting in similar processing times.

5.2. Acknowledgement Ensurance

During the FARM process, in case there is a lot of interference in the transmission channel and the frame still reaches Transceiver B error free, it will send an acknowledgement in the form of a PLCW (if the received frame was a Sequence Controlled frame), which, in turn, is submitted to the same interference in the transmission channel.

Thus, during the transmission of the acknowledgement, an error may occur in the reception. Therefore, measures will have to be taken to prevent this situation.

For example, if Transceiver A does not receive a PLCW in the expected time, Transceiver B will have to retransmit the PLCW frame. In addition, in case the PLCW comes with errors, Transceiver B will also have to retransmit the acknowledge.

The retransmission of a PLCW, illustrated in Figure 5.1, is not included in the protocol and is good addition to future protocol developments.

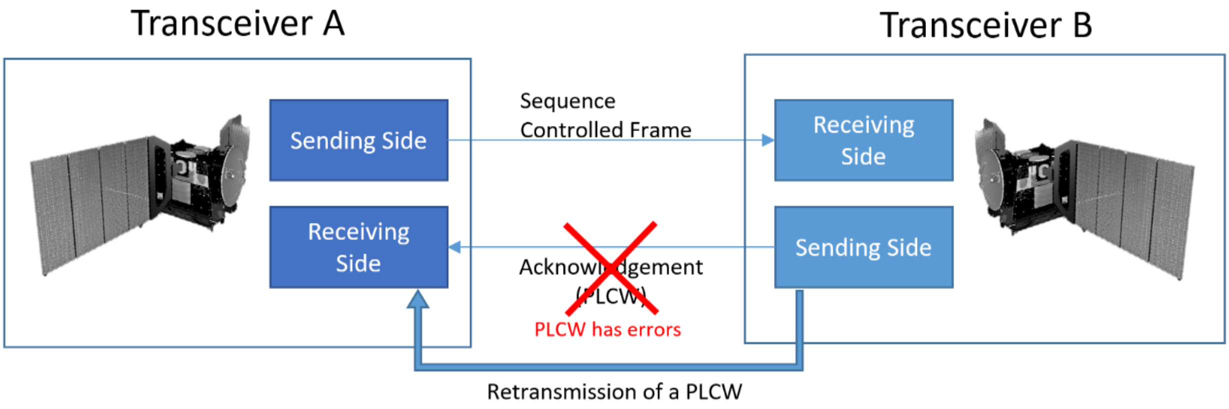


Figure 5.1 – Retransmission of a PLCW.

Moreover, Transceiver A needs to know how many frames Transceiver B received. This information is found on the PLCW, however, if the PLCW contains errors, this information is no longer valid. It can also happen that the PLCW is not received by Transceiver A. For both cases, the next time a PLCW is sent, it will indicate a different number of frames received.

To avoid such situations and ensure that Transceiver A receives the correct information, it is important to ensure that a Sequence Controlled frame is only sent by Transceiver A, when it receives an acknowledgement from Transceiver B, to notify that it has received the frame.

If for some reason the PLCW is not correctly received by Transceiver A, there must be a directive or variable to block further Sequence Controlled frame transmissions until the correct PLCW is received.

Additionally, if, during this period, Expedited frames have been sent, in the new PLCW, this information will be updated with the correct number of frames received on Transceiver B. All in all, a “hold transmission” directive or variable must be issued on Transceiver A sending side while the acknowledge does not arrive.

5.3. Signal Demodulation

Section 4.2 describes the Physical Layer simulations, in particular the attempts on using *Costas Loop* algorithm and *Phase Locked Loop* algorithm to demodulate the received signal. However, these two algorithms are not the most adequate to demodulate the signal.

For the Costas Loop algorithm to work correctly, the residual carrier of the received signal must be previously removed. Regarding the Phase Locked Loop, as Equation 4.13 demonstrates, it was not ideal, as it would require some iterations until the demodulated signal is close to the original message. However, this algorithm is very similar to the solution adopted.

All in all, the process chosen to demodulate the signal is more effective and efficient than the Costas Loop and the Phase Locked Loop algorithms. The best solution to demodulate the signal was the first option described in section 4.2.2.

An important factor to be considered during a signal demodulation is choosing the type of filter. Figure 5.2 compares different types of filters.

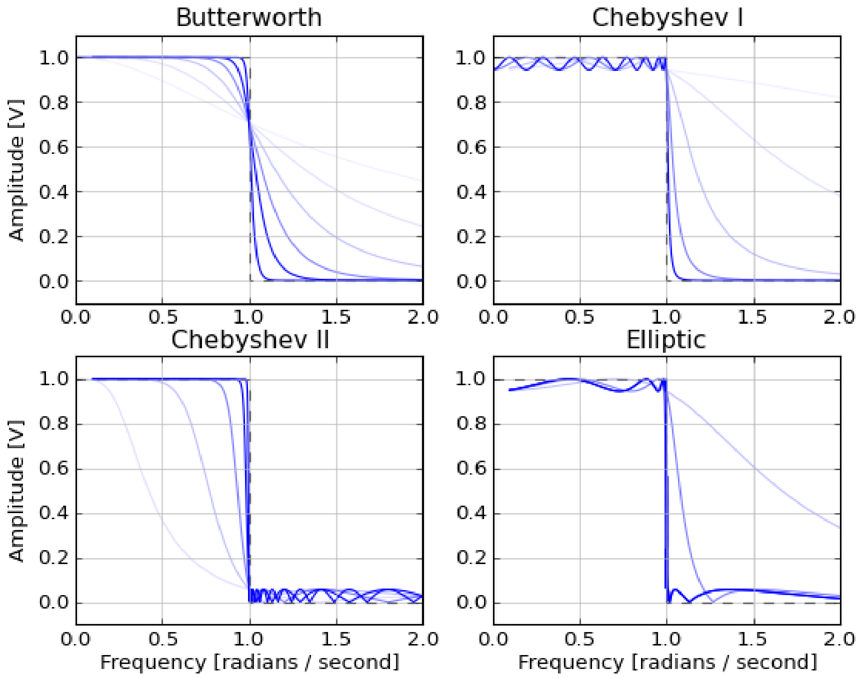


Figure 5.2 – Butterworth, Chebyshev and Elliptic filter design techniques (source: [29]).

Each filter can be a Low Pass, High Pass, Band Pass or Stopband filters. In Figure 5.2, as the blue color intensifies, the order of the filter increases, resulting in a sharper cut-off frequency.

Due to computational efficiency, the higher order filters require more time to filter the signal. The higher the order of the filter, the longer it will take for the filter to process the final resulting signal. Thus, it must be a compromise between a sharper cut-off and the time to process and filter the signal.

In this dissertation, the ones used are the Band Pass Butterworth filter followed by a Low Pass Butterworth filter. The Band Pass Butterworth filter is applied with 1st order, and a band pass of 20 MHz. While the second filter is a Low Pass 4th order Butterworth filter.

Figure 5.3 represents a demodulated signal using both filters mentioned above with the transmitting power signal of 1 W and a Signal to Noise ratio of 5. In Annex G the order of the Butterworth Low Pass filter is changed, in order to see the differences in the filtered signals.

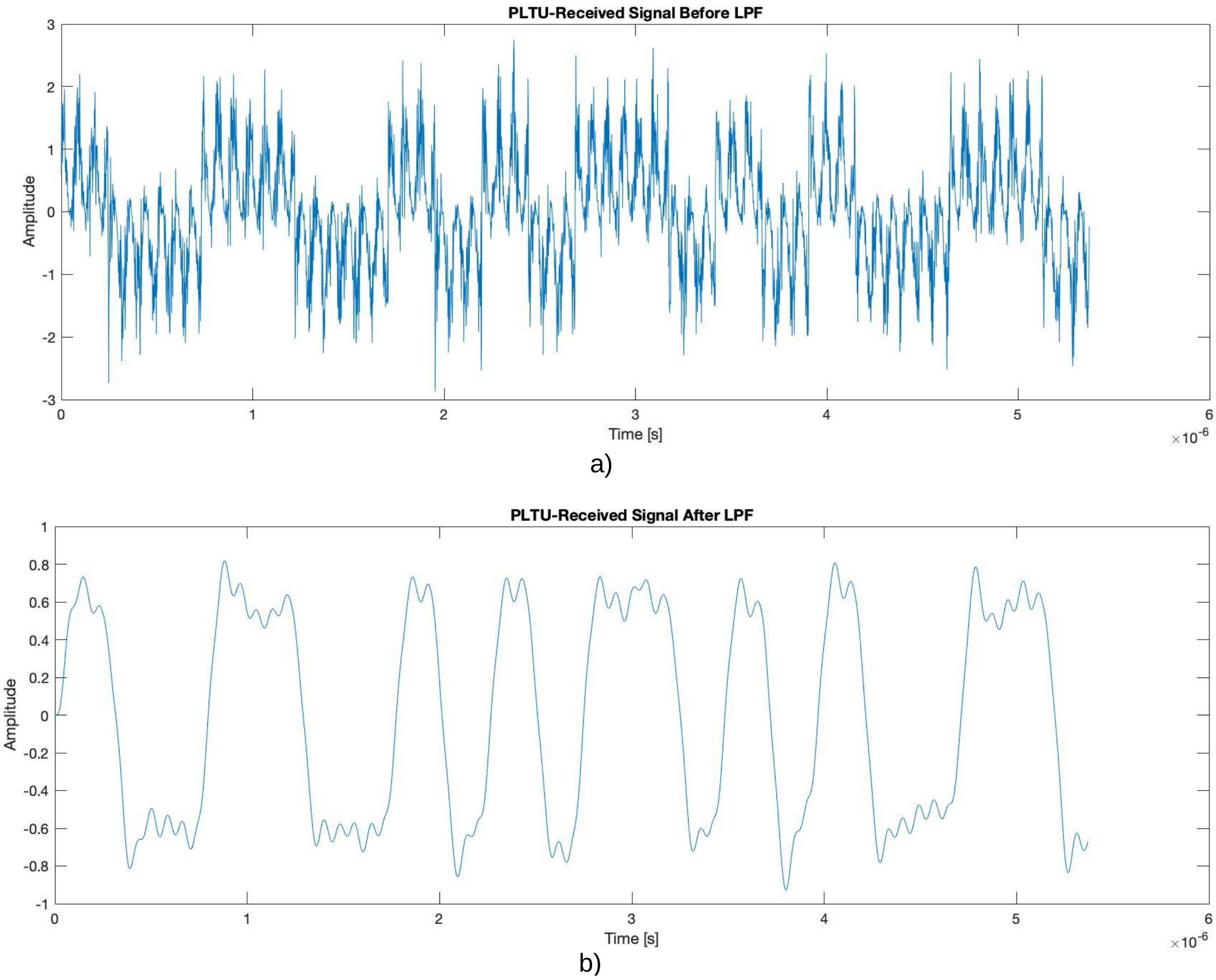


Figure 5.3 – a) Received signal before b) Received signal after a Low Pass 4th order Butterworth filter, respectively.

Regarding the Elliptic filters, the reason behind the non-linear reduction of noise in the filtered received signal as it happens on the previous filters—Butterworth and Chebyshev filters—is the passband and stopband ripple effects, characteristic of the Elliptic filters. Figure 5.4 illustrates the Elliptic filter orders considered in Annex I.

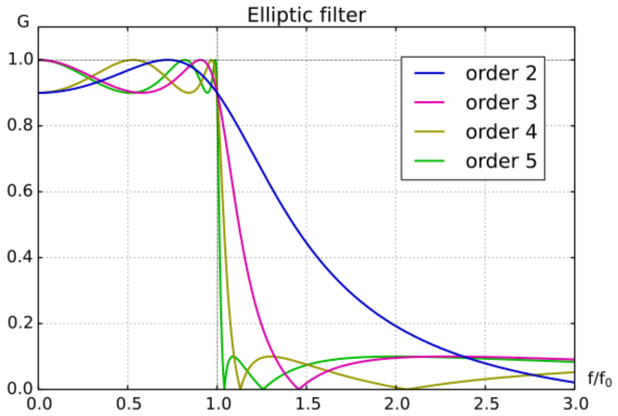


Figure 5.4 – Comparing different orders of Elliptic filters.

In conclusion, the filter used in this MATLAB simulator is the Butterworth filter due to its smooth pass-band and stop-band characteristics, with a 4th order for a sharp cut-off frequency. A higher order will have a sharper cut-off, but the processing time would be higher, compromising the efficiency.

Keep in mind that it is not important to analyze different types of filter techniques for the Band pass filter, as it is only used to reduce the noise around the maximum frequency and it does not affect significantly the demodulated received signal. What matters is the second filter—the Low Pass filter—after multiplying by the artificial sinusoidal signal to remove the doubled frequency, thus obtaining the demodulated message.

5.4. Discussion - Different Scenarios

This dissertation aims to simulate and analyze the data transmission between three space vehicles — orbiter, lander and rover.

In order to bring this simulator closer to reality, it is necessary to take into account several factors such as the planet atmosphere, fading, free space path loss and line of sight, as well as the different transmission powers associated with each of these vehicles.

Basically, it is necessary to consider all possible interferences in the transmission channel and the different characteristics of each vehicle.

5.4.1. Transmitting Power simulating different vehicles

In order to simulate the various space vehicles, the variable under analysis is the transmission signal strength. Depending on the vehicle, the signal strength is different. In case of an orbiter, the signal transmission power is much higher than that of a rover. Consider that the power of an orbiter is 10 times greater than the power of a lander / rover. In Annex J, there are four different stages of the transmitted signal with different transmission powers. There are three use cases, for each space vehicle.

Figure 5.5 a) corresponds to a Rover (since its structure requires a robust moving vehicle, without much space for a powerful transmitting antenna), while Figure 5.5 b) corresponds to a lander (because it has to communicate with the orbiter, corresponding to a longer distance). Lastly, Figure 5.5 c) with a transmitting power of 100 Watts represents the orbiter. These values are experimental to visualize the differences between transmission powers that in turn contribute to a receiving signal with less errors.

In addition, it is important to note that Figures 5.5 have a data bit-length of 11 bits, much less than the 16344 bits[1] that a Version-3 Transfer Frame can carry. The reason is to simplify and make the figures understandable to enhance the variations in signal transmission power.

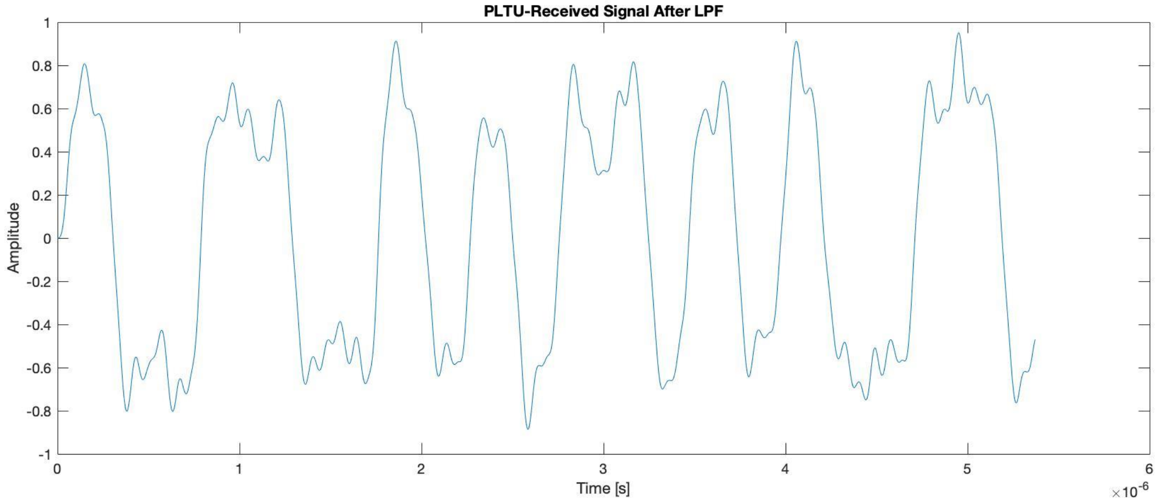
---

[1] One byte corresponds to 8 bits. Therefore, 2043 bytes correspond to 16344 bits.

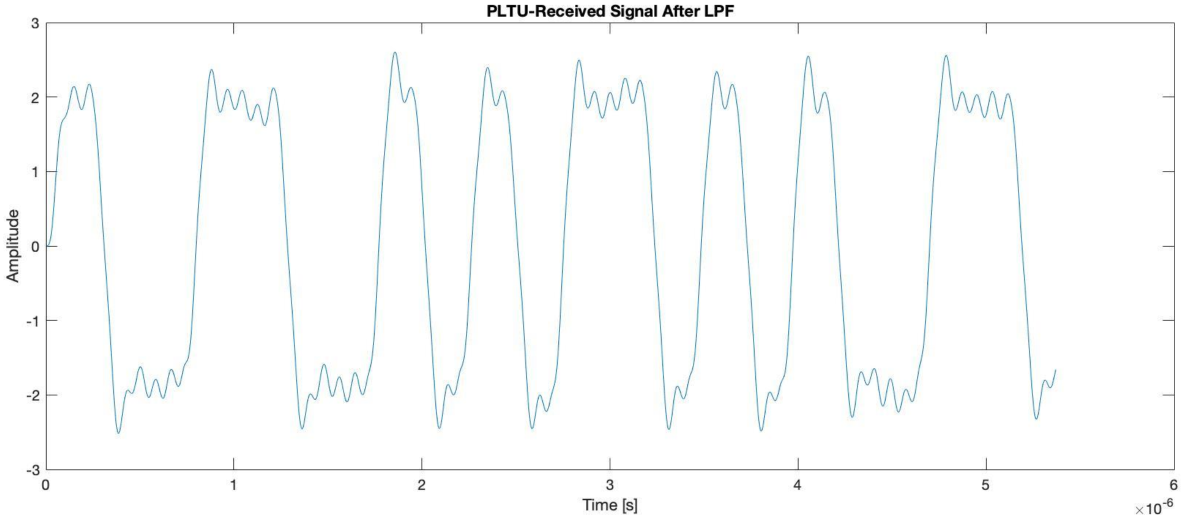
Considering the Equation 4.1 outlined in section 4.2.1 the transmitted power is modulated by $\sqrt{2\mathbf{P_t}}$.

$$\mathrm{mSig(t)} = \sqrt{2\mathrm{P_t}}\,\sin(2\pi \mathrm{f_c t} + \beta \mathrm{m(t)} + \theta_c) \tag{4.1}$$

So, the amplitude signals seen on Figures 5.5 are expected. Although the amplitude of the received signal is approximately 0.7 W in Figure 5.5 a), the receiving transceiver is still able to demodulate the signal without errors. The SNR considered was zero. The noise in the transmission channel is responsible for an increase of the signal amplitude. The Low Pass filter eliminates the excess signal amplitude created by the noise in the transmission channel.



a)



b)

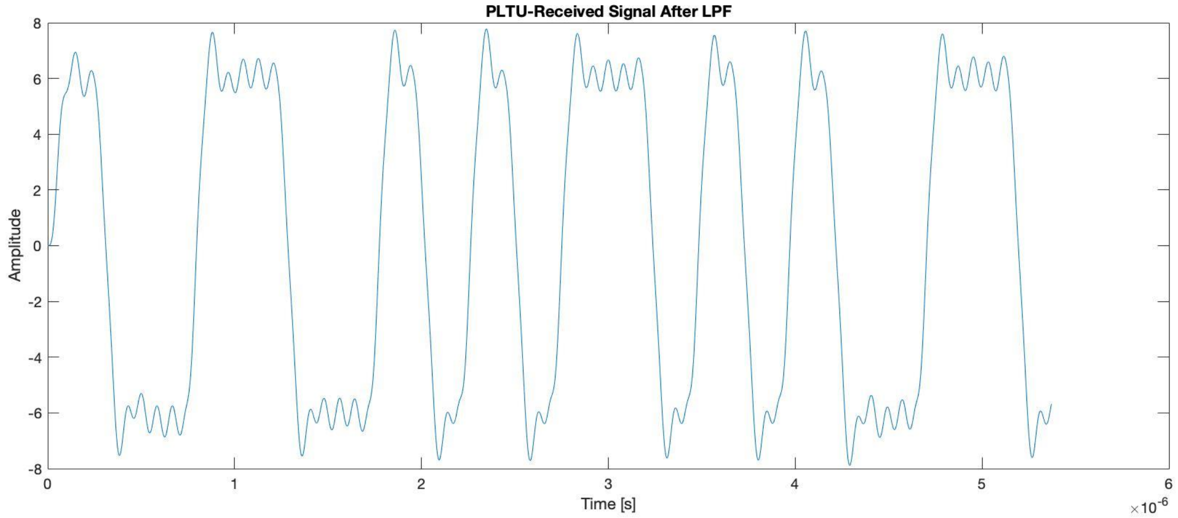


Figure 5.5 – Received Signal with different transmitting powers.
a) $\mathrm{P_t} = 1\,W$; b) $\mathrm{P_t} = 10\,W$; c) $\mathrm{P_t} = 100\,W$.

5.4.2. Transmission Channel – Different Scenarios

In the transmission channel, there are three external factors that affect the signal, these are: Free Space Path Loss (FSPL), Fading and Line of Sight.

Free Space Path Loss

Free space path loss occurs to the electromagnetic waves, when propagating in the atmosphere, suffering an opposition directly proportional to the distance it travels. Considering isotropical antennas ($\mathrm{G_s} = \mathrm{G_r} = 0\,dB$), the free space path loss (L_{fs}), represented in Equation 5.3, is based on Friis equation represented in Equation 5.2.

$$\lambda_{[m]} = \frac{c}{f_{[Hz]}}\ ;\ \ \mathrm{c} = 3 \times 10^8\ \mathrm{m/s} \tag{5.1}$$

$$\frac{\mathrm{P_r}}{P_t} = G_r G_t \left(\frac{\lambda}{4\pi d_{[m]}}\right)^2 \tag{5.2}$$

$$L_{fs} = -10\log\left(\frac{\lambda}{4\pi d_{[m]}}\right)^2 \quad [\mathrm{dB}] \tag{5.3}$$

From Equation 5.3, it is possible to calculate the free space path loss. The frequency may vary from 435,6 MHz to 450,0 MHz on the send side, while the return frequency varies from 390 MHz to 405 MHz. These frequency amplitudes do not interfere significantly to the signal attenuation. However, the distance between transceivers is an important factor that affects the transmitted signal. There are three different scenarios for each communication session.

The first scenario considers an Earth orbiter establishing a communication session with a Mars orbiter, corresponding to a distance of $54{,}6 \times 10^6\ km$. From the sending side, the free space path loss has an attenuation of 240 dB, and an attenuation of 239 dB corresponding to the return channel. On the other hand, if the two planets are on opposite sides of the sun, the maximum distance is approximately $400 \times 10^6\ km$. Then, for the maximum forward link frequency channel – 450 MHz, the free space path loss is 257.7 dB, and, when considering the minimum return link frequency channel – 390 MHZ, the attenuation is of 256.3 dB. For more details, see reference [16].

The second scenario is a communication link established between a Mars orbiter and a lander. The distance considered between the two transceivers was 255 km, which is the same distance as a previous Mars Mission called *Mars Reconnaissance Orbiter*, which established successfully a relay communication back to Earth. In this mission, the orbiter arrived at Mars orbit in 2006 and it is still currently operating (Source [14]).

In this scenario, where the orbiter is directly above the lander, the FSPL is approximately 133,0 dB (depending on the frequency channel: for 390 MHz, it corresponds to 132,4 dB; while for 450 MHz, it corresponds to a FSPL of 133,6 dB).

In addition, it must be taken into consideration the line of sight between the orbiter and lander, since the orbiter is not in a geostationary orbit. This is represented in Figure 5.6.

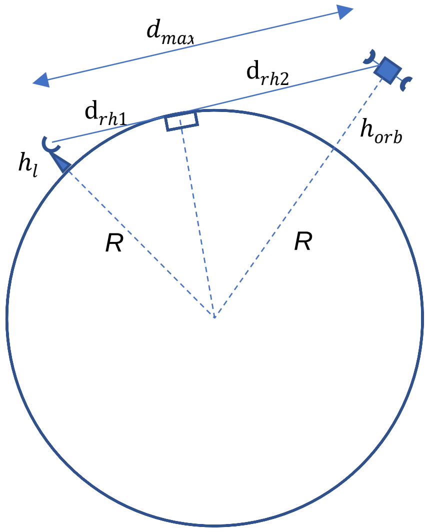


Figure 5.6 – Line of sight between a lander and an orbiter.

The maximum distance capable of establishing a communication session link is d_{max}.

$$d_{max} = d_{rh1} + d_{rh2} \tag{5.4}$$

$$(R + h_1)^2 = R^2 + \mathrm{d}_{rh1}{}^2 \tag{5.5}$$

$$\mathrm{d}_{rh1} = \sqrt{2Rh_1} \qquad (R \gg h_1) \tag{5.6}$$

$$(R + h_{orb})^2 = R^2 + \mathrm{d}_{rh2}{}^2 \tag{5.7}$$

$$\mathrm{d}_{rh2} = \sqrt{2Rh_{orb}} \qquad (R \gg h_{orb}) \tag{5.8}$$

Considering that Mars radius is 3389,5 km, the height of the lander is 5 m, and the height of the orbiter from Mars surface is 255,0 km, the maximum distance is 1320,6 km. Thus, the FSPL, in this scenario, is 146,7 dB (for a frequency channel of 390 MHz) and 147,9 dB (for a frequency channel of 450 MHz).

Thirdly, the last scenario corresponds to a communication link established between a lander and a rover on Mars surface. In this case, similarly to the previous scenario and due to Mars round surface, it also must be taken into account the line of sight between both transceivers. There is a maximum distance where the lander can no longer maintain a communication session with the rover, since it is not on lander sight anymore.

Figure *5.7* illustrates how far the horizon is from the lander antenna (radio-horizon distance - d_{rh}), as well as the maximum distance between the rover and lander antennas in order to keep a line of sight among both transceivers - assuming the antennas are at the same height.

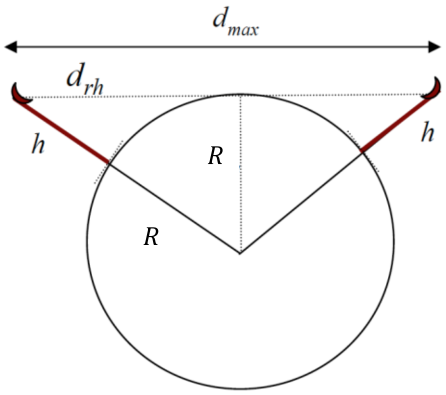


Figure 5.7 - Radio horizon distance (source: Telecommunications Systems, IST. Chapter Feixes Hertzianos slide 31)

Equations 5.9 and 5.10 represent the line of sight formula, where *R* represents Mars radius, and *h* the height of the antenna. Moreover, this formula assumes there are no relevant obstacles interfering with the signal between the antennas.

$$(R+h)^2 = R^2 + \mathrm{d}_{rh}{}^2 \tag{5.9}$$

$$\mathrm{d}_{rh} = \sqrt{2Rh} \qquad (R \gg h) \tag{5.10}$$

Considering Mars radius to be 3389,5 km, the radio-horizon distance (d_{rh}) is 5.8 km. If the Rover antenna has the same height as the Lander, the maximum horizon distance is twice the d_{rh} (11.6 km).

Therefore, the FSPL for the third scenario is 106,8 dB (for a frequency channel of 450 MHz) and 105,6 dB (considering a 390 MHz frequency channel). For more detail please see reference [15].

As expected, the Free Space Path Loss increases with the distance between transceivers.

Table 5.1 – Free space path loss for different scenarios.

Scenarios	L_{fs} for **Forward Channel Frequency (450 MHz)**	L_{fs} for **Return Channel Frequency (390 MHz)**
Earth orbiter - Mars orbiter (400×10^6 km)	257,5 dB	256,3 dB
Earth orbiter - Mars orbiter ($54,6 \times 10^6$ km)	240 dB	239 dB
Mars orbiter – Lander/Rover (1320,6 km)	147,9 dB	146,7 dB
Mars orbiter – Lander/Rover (255 km)	133,6 dB	132,4 dB
Lander – Rover (11,6 km)	106,8 dB	105,6 dB

Fresnel Ellipsoid and Elevation Angle

Considering the scenario of a communication link established between a lander and an orbiter as illustrated on Figure 5.8, it is a reasonable approximation to neglect the height of the lander compared with the height of the orbiter. Therefore, when the orbiter is the farthest apart from the lander, but still in line of sight, it might be considered a zero degree elevation angle.

However, in order to avoid nearby interferences by the surrounding terrain roughness, it is enough to have an elevation angle of five degrees. If the angle of the lander antenna is negative, the signal will not reach the orbiter with the desired strength.

If the angle of transmission is five degrees, the less likely it is to have objects interfering with the Fresnel ellipsoid. In contrast, if it is considered a zero degree transmission angle, half the Fresnel ellipsoid is blocked by Mars' surface and hence the signal power is reduced by a quarter of its value (in the best-case scenario).

To calculate the radius of Fresnel ellipsoid between the antennas, Equation 5.11 is used, where n is the obstacle number at distance d_k, while *d* is the total distance between antennas and λ is the wavelength ($\frac{c}{f}$).

$$r_{[m]} = \sqrt{\frac{n \times \lambda \times d_k(d - d_k)}{d}} \tag{5.11}$$

For the distance (d_k) closer to the lander, the ellipsoid radius is not intersected by Mars surface, considering the antenna is not obstructed by considerable obstacle.

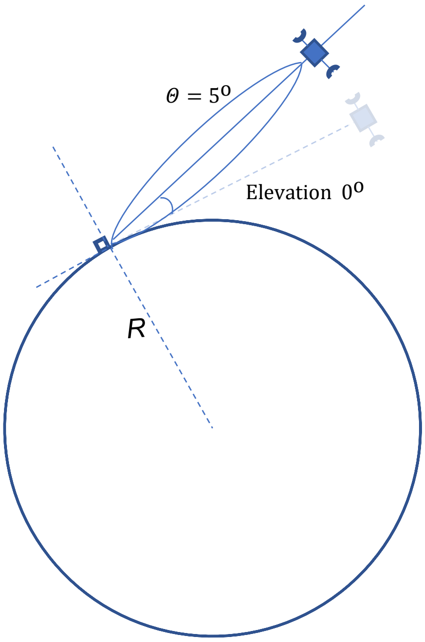


Figure 5. 8 - Representations of Fresnel ellipsoid and transmission angle for a communication session between a lander and an orbiter.

Accounting for the transmission angle of 5 degrees and the landers antenna having 5 m height, the Fresnel ellipsoid does not contribute for the signal attenuation in this scenario – similar to an open plain - where the terrain allows it.

Fading and Mars Atmosphere

Another external factor to be taken into consideration is fading. This phenomenon is the fluctuation of the signal amplitude between the sender and the receiver, caused by variations in the medium where electromagnetic waves propagate.

On the previous subsection, the scenarios considering a communication session between two orbiters, fading did not affect significantly the signal. In contrast, the other two scenarios—a communication session between an orbiter and a lander/rover, and between a lander and a rover—suffer considerably from fading.

There are two types of fading: power fading, corresponding to slow variations in the received signal, associated with atmospheric disturbances; and multipath fading, corresponding to fast variations in the received signal, due to the signal reaching the receiver from different paths.

These different fading attenuation factors are translated into three different probability density distribution functions: Log-Normal (slow fading), Rice (fast fading, low intensity) and Rayleigh (fast fading, high intensity). These distribution functions are adapted to Earth like conditions.

According to NASA (reference [16]), Earth and Mars have an atmosphere and ionosphere where radio waves suffer attenuations while propagating through them. At Mars the major attenuation factor is dust storms, which affects mostly frequencies around 32 GHz, with an attenuation of 3 dB (not relevant for the frequencies used in Proximity-1 protocol, around 400 MHz as described in previous subsections).

Moreover, this type of storm is rare. Under normal conditions, a storm only attenuates the signal 1 dB. Additionally, there are no rain observation reports on Mars. In case there is rain in the planet, it would be so light that it would not cause significant attenuation to radio waves.

The tropospheric losses - gaseous attenuation, cloud, fog, tropospheric scattering – scintillation and turbulence - account only 0.4 dB losses for frequencies around 32 GHz, which causes no considerable attenuation for frequencies around 400 MHz. Regarding the Martian ionosphere, there is also some absorption and scintillation effects on very high frequencies (VHF) - 100 MHz to 500 MHz - around 0.5 dB. Comparing to Earth, the Martian ionosphere is one order of magnitude thinner.

Multipath fading on Martian surface must also be taken into consideration. Mars surface has rocks and hilly structures, reported by previous Mars missions (Pathfinder and Viking), that cause reflections on the radio waves, resulting in multipath fading phenomenon.

Extrapolating from Earth-based experiments on similar rocky surfaces, the attenuation ranges from 2 to 7 dB for 870 MHz wave frequencies. So, for a lower frequency (400 MHz) it is expected to have a lower attenuation. Table *5.2* sums up the major contributions for Mars radio wave attenuations.

Usually, during space communications, there is a margin of 2% where the signal is interrupted. Half of these 2% corresponds to damaged material and atmospheric conditions; the other 1% is due to other causes (reference [18]).

Other attenuations might occur when a communication session is established between an orbiter and an Earth-based space station. In this case, the signal suffers an attenuation in the ionosphere. In this simulation, these scenarios were not considered, however to see in detail, please see reference [19]. .[1]

Table 5.2 – Martian radio wave attenuation for very high frequencies.

	VHF (100 MHz – 500 MHz)
Ionosphere (absorption and scintillation)	0.5 dB
Troposphere (scattering)	0
Gaseous	0
Cloud	0
Rain	0
Fog	0
Aerosol (haze)	0
Dust (worst case)	0.1 dB
Total Vertical Losses	0.6 dB
Multipath (for 870 MHz)	2-7 dB

---

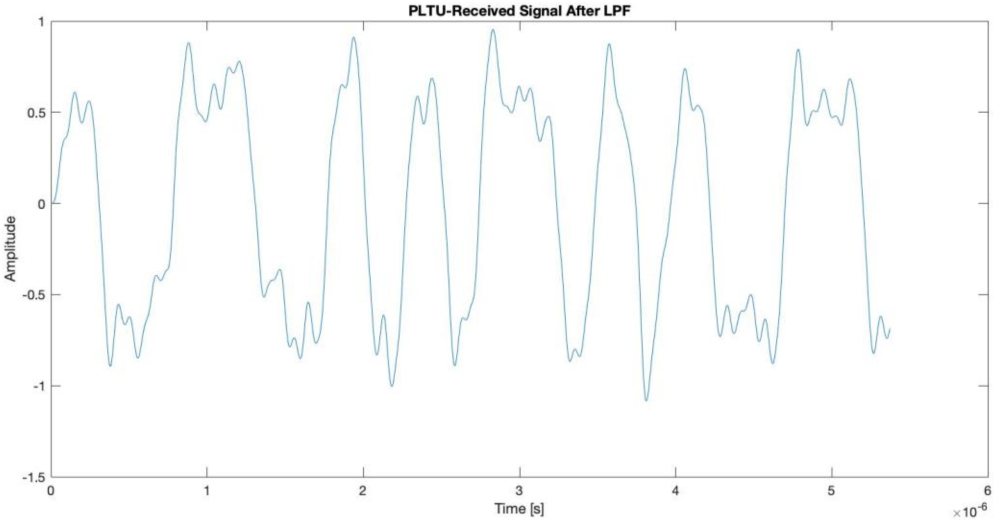
[1] In this simulation, the medium loss through interplanetary space is ignored.

Signal to Noise Ratio

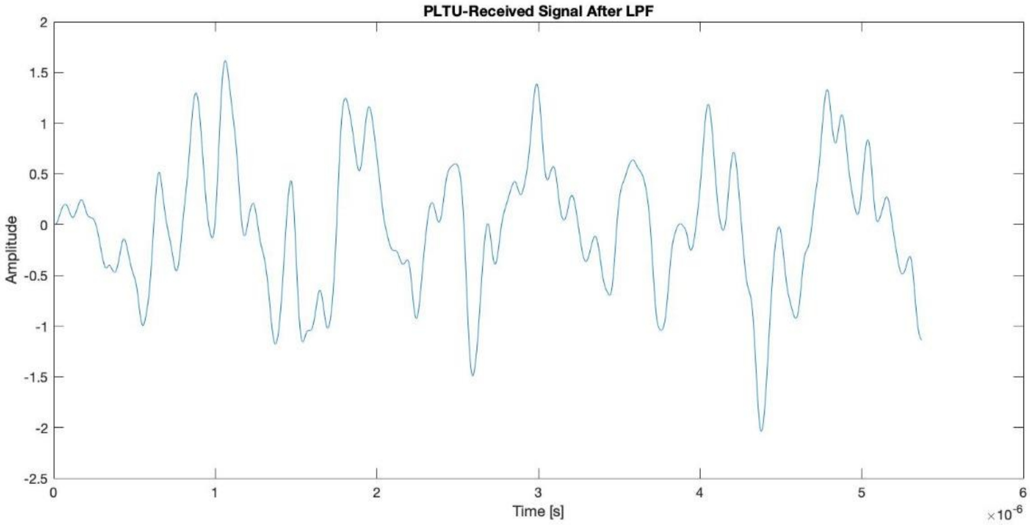
The signal to noise ratio (SNR) is an important factor to simulate the transmission channel. The SNR may be calculated using the following Equation:

$$\mathrm{SNR} = \frac{P_{signal}}{P_{noise}} \tag{5.12}$$

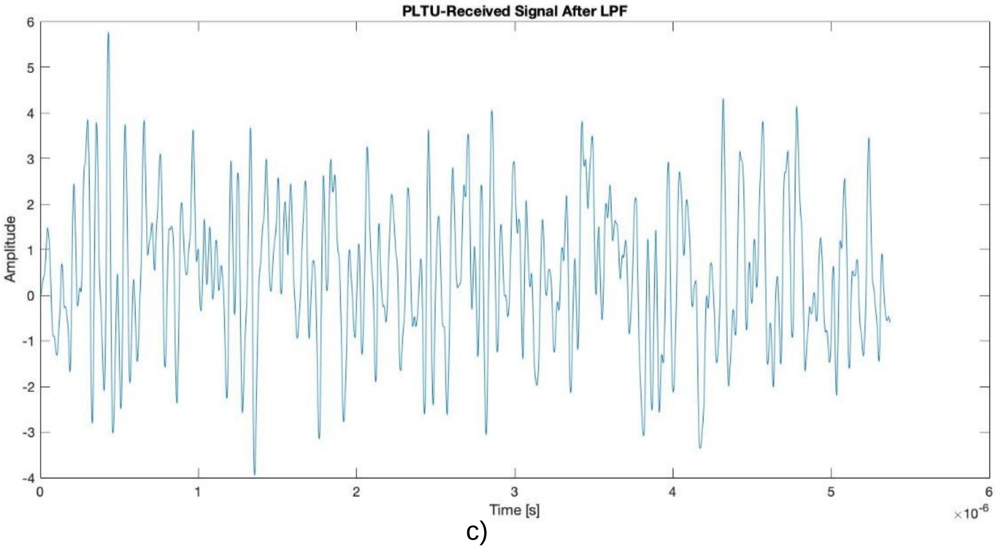
For example, a signal to noise ratio of 3 dB, means that the signal power is twice the noise power. Thus, the higher the SNR, the better. Figures 5.9 are the output of three simulations with the same signal but passing through different transmission channels with higher SNR values. The following figures refer to the received signals with decreasing values of SNR.



a)



b)



c)

Figure 5.9 – Received signals with different signal to noise ratios and transmitted power (Pt = 1 W)

a) SNR = -3 dB; **b)** SNR = -12 dB; **c)** SNR = -18 dB.

In Figure 5.9 there are three simulations of the received signal, after passing through different transmission channels with decreasing SNR values. From all three received signals, the first two were detectable by the receiver error free. Figure 5.9. c) was discarded by the receiver, since the cyclic redundancy check — process to verify the error frames — did not approved the frame. The process is detailed in Annex C. Furthermore, Figure 5.9 considers a PLTU with a ten-bit length, for simplicity reasons and to have a better visibility on the received PLTU signal.

Signal to Noise ratio can also be viewed as the ratio of mean to standard deviation of a signal.

$$\mathrm{SNR} = \frac{\mu^2}{\sigma^2} \tag{5.13}$$

In Equation 5.13, μ refers to the signal amplitude, and σ to the noise standard deviation. On the following Equations, there is a demonstration of the variation of the signal amplitude *y* depending on the number of samples *N* (the full demonstration is detailed in Annex F).

$$\mathrm{y} = \frac{1}{N}\sum_{i=1}^{N} x_i \quad , \qquad \mathrm{x}_i \ \text{v.a. iid } \mathrm{N}(\mathrm{m}_x, \sigma_x{}^2) \ \ ^{[1]} \tag{5.14}$$

$$\begin{aligned} \mathrm{m}_y &= E[y] \\ &= E\left[\frac{1}{N}\sum_{i=1}^{N} x_i\right] \\ &= m_x \end{aligned} \tag{5.15}$$

---

[1] **v.a** = random variable; **i.i.d**. = independent and equally distributed.

$$\sigma_y{}^2 = E\left[\left(y - m_y\right)^2\right] \tag{5.16}$$
$$= E[y^2] - m_y{}^2$$

$$E[y^2] = E\left[\frac{1}{N}\sum_{i=1}^{N} x_i \cdot \frac{1}{N}\sum_{j=1}^{N} x_j\right] \tag{5.17}$$
$$= \frac{1}{N^2}\sum_{i=1}^{N}[\,(\mathrm{N}-1).\,\mathrm{m}_x{}^2 + \sigma_x{}^2 + m_x{}^2]$$

Considering that $[x_i].E\left[x_j\right] = m_x{}^2$; $E[x_i{}^2] = \sigma_x{}^2 + m_x{}^2$; and that $\sum_{\substack{i=1\\ j\neq i}}^{N} E[x_i x_j]$ is true for N-1 cases, while $E[x_i{}^2]$ only happens once, it is possible to simplify to:

$$E[y^2] = \frac{1}{N^2}\sum_{i=1}^{N}[\,\mathrm{N}.\,\mathrm{m}_x{}^2 + \sigma_x{}^2] \tag{5.18}$$
$$= \frac{1}{N^2}\left[\,\mathrm{N}^2.\,\mathrm{m}_x{}^2 + N.\sigma_x{}^2\right]$$
$$= \mathrm{m}_x{}^2 + \frac{\sigma_x{}^2}{N}$$

Joining Equations 5.16 and 5.18,

$$\sigma_y{}^2 = E[y^2] - m_y{}^2 \tag{5.19}$$
$$E[y^2] = m_X{}^2 + \frac{\sigma_x{}^2}{N} \tag{5.20}$$

Knowing that $m_y{}^2 = m_x{}^2$, it is possible to conclude that:

$$\sigma_y{}^2 = \mathrm{m}_x{}^2 + \frac{\sigma_x{}^2}{N} - m_y{}^2 \tag{5.21}$$
$$= \frac{\sigma_x{}^2}{N}$$

This result ensures that if the number of samples grows, the standard deviation decreases. Meaning that the noise decreases with the increase of number of samples represented on a bit. So, for example, if it is considered a 10 sample (N=10), the SNR increases 10 dB ($10^{\frac{\mathbf{10\,dB}}{10}} = 10$) comparing with a single sampled simulation.

Therefore, the following Figure 5.10 considers four different samplings in order to analyze the percentage of the error-free received frames. The yellow line represents the higher number of samples per bit (3000, 1 bit corresponds to three carrier wave periods, and each carrier wave period has 1000 samples). As expected the yellow line has better resilience than the other simulations tested with a smaller number of samples.

Figure 5.10 illustrates the percentage of error received frames by Transceiver B while varying the signal to noise ratio. As expected, by decreasing the signal to noise ratio, the percentage of error received frames increases, although not linearly. Figure 5.10 is the result of over 6000 transmission-frame simulations (one hundred or more for each value of SNR).

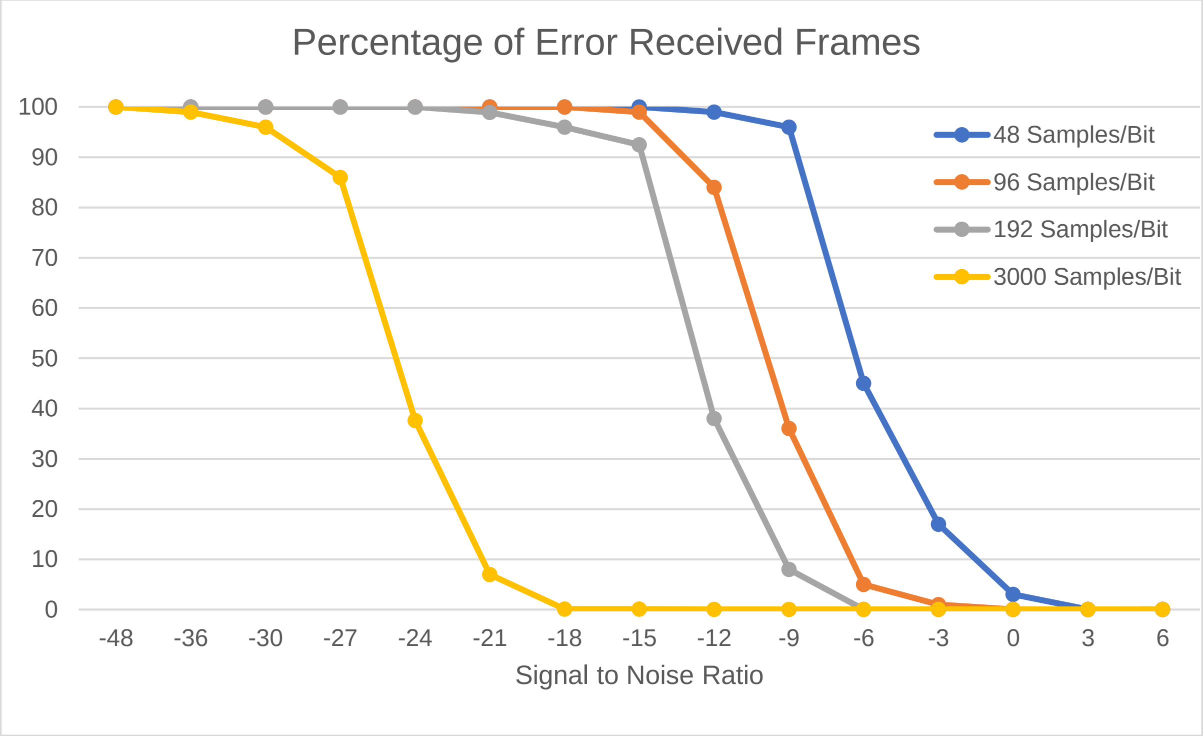


Figure 5.10 – Percentage of error received frames with different signal to noise ratios with a fixed transmitted power (Pt = 1 W).

By analyzing Figure 5.10, one can conclude that depending on the number of samples per bit, the signal to noise ratio is different for each case. As expected, for the same number of samples per bit, the increase of the signal to noise ratio leads to fewer error frames received. Moreover, as the number of samples per bit increases, the fewer error frames received for the same SNR. In addition, the three curves (grey, orange and blue) representing different samples per bit are shifted 3 dB from one another due to the value being doubled.

On the following equations, L_{fs} stands for the free space path loss attenuation, while L_a represents the atmosphere attenuation plus fading losses.

$$P_r[\text{dBW}] = P_t[dBW] + G_r[dBi] + G_t[dBi] - L_{fs}[\text{dB}] - L_a[\text{dB}] \tag{5.22}$$

$$L_{fs}[\text{dB}] = 10\ log_{10}\left(\frac{\lambda}{4\pi d}\right)^2 \tag{5.23}$$

$$P_r[\text{dBW}] = 10\ \ log_{10}(P_{[W]}) \tag{5.24}$$

Considering Tables 5.1 and 5.2, it is possible to estimate what is the received power by the receiving antenna for the different scenarios.

Furthermore, it is considered an antenna gain of 0 dBi for the receiver and a gain of 0 dBi for the transmitter. Usually, some antennas might consider a gain of 3 or more dBi, but these antennas are directional antennas, such as *Yagi Uda*, which radiate or receive greater power signal in a specific direction. Although these directional antennas can increase an antenna performance, a slight change in the direction occurs and the power signal decreases substantially.

It is considered a 5 dB attenuation for fading plus atmosphere attenuation. According to NASA (see reference [17]), a rover antenna usually has a gain of around 1.4 dBi; although in this simulation it is considered an antenna gain of 0 dBi.

In addition, an antenna transmitting power should be strong enough to surpass all the attenuations the transmission channel encounters. According to [18] *Chapter 5* and *Chapter 8*, the Effective Isotropic Radiated Power (EIRP) is:

$$EIRP = P_t + G_t \tag{5.25}$$

For a transmitted power of 150 W and an antenna gain of 0 dBi, the EIRP is 21,76 dBW. Taking into account Equation 5.22 the received power was computed for different scenarios, which are represented in Table 5.3.

Table 5.3 – Received signal strength for different scenarios.

Scenarios	$\boldsymbol{P_r[dBW]}$	$\boldsymbol{P_r[W]}$
Earth orbiter - Mars orbiter ($\mathbf{400 \times 10^6}$ km)	-240,74	$\mathbf{8 \times 10^{-25}}$
Earth orbiter - Mars orbiter ($\mathbf{54,6 \times 10^6}$ km)	-223,24	$\mathbf{4,74 \times 10^{-23}}$
Mars orbiter – Lander/Rover (1320,6 km)	-131,14	$\mathbf{7,69 \times 10^{-14}}$
Mars orbiter – Lander/Rover (255 km)	-116,84	$\mathbf{2,07 \times 10^{-12}}$
Lander – Rover (11,6 km)	-90,04	$\mathbf{9,9 \times 10^{-10}}$

The received signal strength is very low. Nonetheless, these values were expected. For space communications, free space path loss has a huge impact on the signal attenuation, since the signal travels distances of hundreds or thousands of kilometers.

In order to intensify the received signal strength, enabling a communication session between transceivers, it should be considered more directive antennas and amplifiers to the receiving transceiver (detailed on page 411 of reference [18]).

Failure Rate

During this simulation, Mean Time Between Failure (MTBF) was not considered. Since this dissertation is based on a MATLAB simulation, and not on hardware implementation, thus, not being able to account for equipment failures. [1]

Sampling Rate

This subsection demonstrates how the sampling rate influences the simulation performance, in particular the modulation and demodulation processes. Since the beginning of this dissertation, it is considered that 1 bit requires three wave periods to be represented, and each wave period is represented by 1000 sample units. Therefore, as 1 bit has 3000 sample units, it requires a high performance, complex and robust software and hardware to support the transmission for this amount of information — considering that a PLTU can go up to 2056 bytes (16448 bits). To remove this demanding necessity (although ideal, but not realistic scenario), one must lower the number of samples per bit.

Considering that, 5 samples are the least number of samples that can represent one bit carrier wave period, as Figure 5.11 illustrates, the maximum frequency cannot be obtained when demodulating the signal. The number of samples is not enough to get the exact value of the maximum frequency, as shows Figure 5.12. The same happens when using 16 samples to represent one period of a carrier wave, represented in Figure 5.13. The maximum frequency obtained is 435,5 MHz instead of the 435,6 MHz that correspond to the first frequency channel number for forward communications.

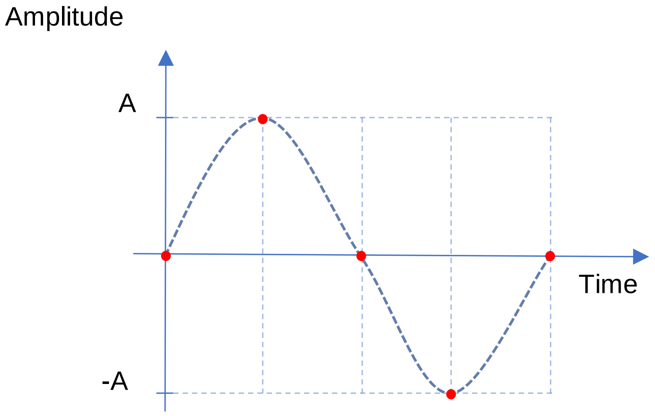
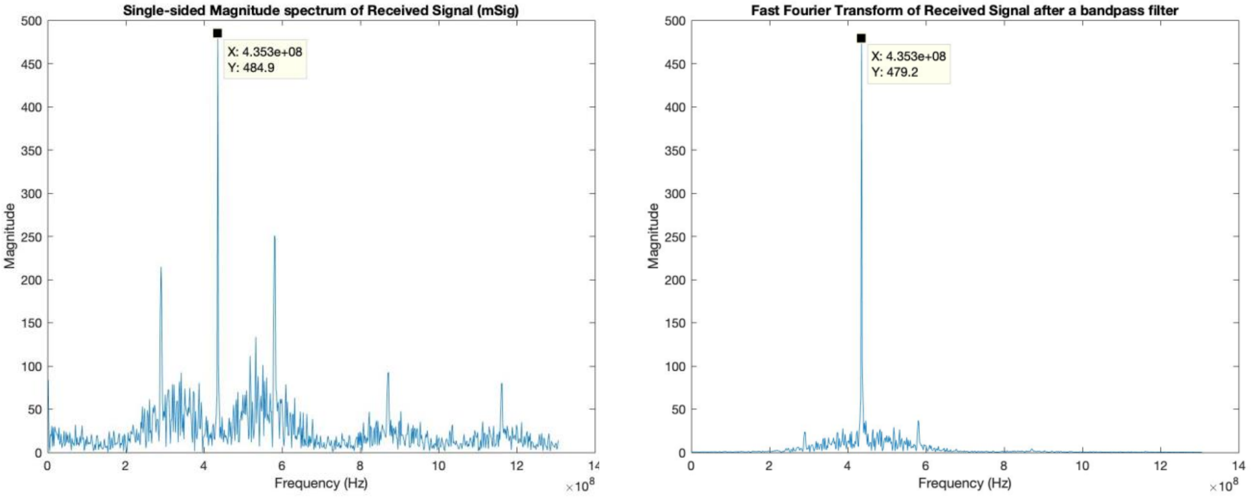


Figure 5.11 – One carrier wave period represented by 5 samples

For a 5 sample per carrier wave period, results on the following Figures:

---

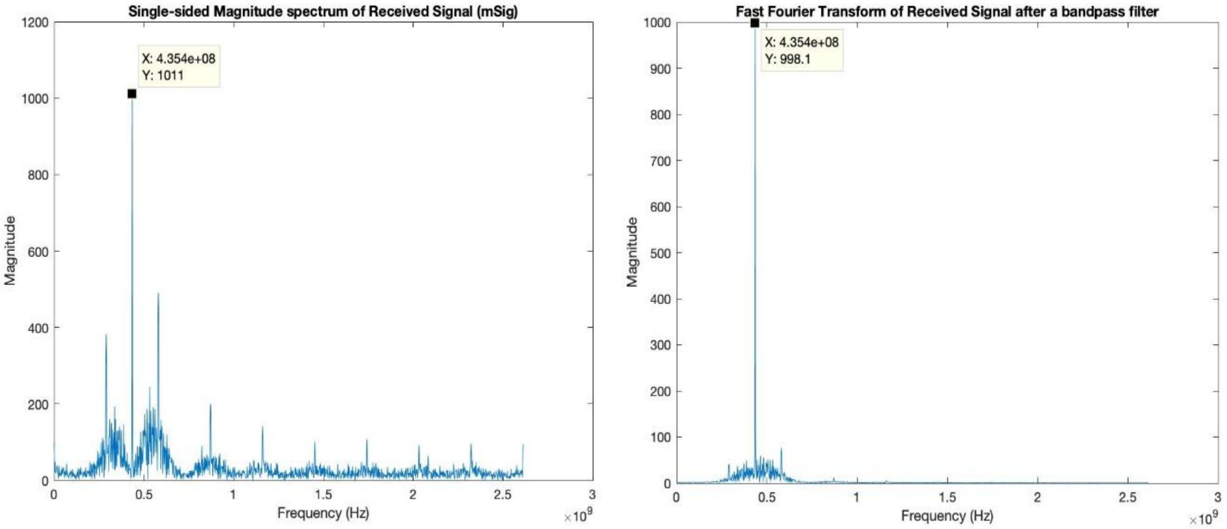
[1] To a detailed understanding of Failure rate, see chapter 13 of reference [18].



a) b)

Figure 5.12 – a) Single sided magnitude spectrum of the modulated signal before a Bandpass filter; b) Single sided magnitude spectrum of the modulated signal after a Bandpass filter.

For a 12 sample per carrier wave period, results on the following Figures:



a) b)

Figure 5.13 - a) Single sided magnitude spectrum of the modulated signal before a Bandpass filter; b) Single sided magnitude spectrum of the modulated signal after a Bandpass filter.

Reducing the number of samples substantially has consequences. The maximum frequency is not correctly obtained when applying a Fourier Transform to the received signal. The frequency is slightly deviated from the transmission frequency. If the Signal to Noise Ratio is high enough the signal can be demodulated. However, if the SNR reduces, the demodulation process becomes less likely to be successful, without error frames.

5.5. Operational Issues

In this section, an enumeration is made of some operation issues that arose during the MATLAB implementation. The fact that a Sequence Controlled frame requires an acknowledgement to be able to send the message to the remote transceiver, causes a delay in the communication channel. In a way, it causes a congestion in the waiting queue between sublayers. Thus, as a waiting queue has limited storage, it might reach a point where there is no storage left to allocate the Sequence Controlled frame and it has to be discarded. This is not only an operational problem but also harms the efficiency of data throughput transmission.

There are other parameters that affect the data transmission efficiency, such as asymmetric data rates between transceivers, the frame lengths and the maximum transmission window size. These operational issues are well described in Annex D.

A setback in the protocol Proximity-1 is the time delay when a Sequence Controlled frame is sent from A to B, and the acknowledge from B has a retransmit flag set to *true*, meaning Transceiver A must retransmit the Sequence Controlled frame again. This happens when Transceiver B receives an error frame, that is immediately discarded, and the process of retransmitting the frame begins (in case it has a Sequence Control quality of service). This delay cannot be avoided. The delay is 3029 Tics, which corresponds to retransmitting the Sequence Controlled frame. The delay only does not account for the acknowledge sending time from B to A. Thus, the delay includes the processing time from Data Services Sublayer Transceiver A sending side until the Data Services Sublayer Transceiver B receiving side, it does not include the I/O Sublayers, because the Frame Acceptance and Reporting Mechanism (FARM) process is managed in the Data Services Sublayer.

5.6. Future Developments and Recommendations

This protocol is called a single master topology, because the frame header can only address the source or the destination node, but not both. One future development might be to include the source and destination addresses, in order to allow operating in a multicast topology.

Another interesting development would be to include in Proximity-1 protocol different scenarios for one-to-one topologies. There is the case where there are multiple one-to-one links, and each operates independently because each link has its own dedicated frequency channel pair. However, it might be useful to have a more dynamic environment, where there are separate hailing and working channels. Sharing a common hailing channel allows any spacecraft to contact any other spacecraft in that enterprise that uses the protocol Proximity-1 recommended standards. Switching to a separate working channel is necessary because this releases the shared hailing channel to be used by either spacecrafts.

For a dynamic environment, assuming there are two landers and two orbiters, and that Orbiter 1 wants to establish a one-to-one link with Lander 1 and Orbiter 2 with Lander 2. However, both orbiters decide to initiate the hailing process at almost the same time. The outcome will be one of two scenarios: either both hailing messages collide, or there is only one corrupted message. In case one hailing starts before the other, a carrier sensing mechanism allows the second caller to back-off the hailing attempt and avoid collision. Then, the second orbiter has two options, it either starts hailing only when the first transmitting orbiter terminates its communication link, or it starts hailing in a different channel frequency. Both are valid options, although the second case is more complex than the first. The above-mentioned “carrier sensing mechanism” would be a good improvement for the Proximity-1 protocol.

6. Conclusion

The investigation and application of protocol Proximity-1 proved to be able to establish a reliable communication session between two transceivers during a final approach to Mars.

Regarding the Physical Layer, the best way to demodulate the signal was not through the Costas Loop Algorithm, nor the Phase Locked Loop, but by applying a simpler and more effective demodulation process. Just apply a Band Pass filter to obtain the maximum frequency of a Fast Fourier transform of the received signal, and then apply a phase detector. Then an artificial carrier wave (with the same frequency and phase) is multiplied by the received modulated signal. Finally, a Low Pass filter is applied to obtain the transmitted message demodulated.

Data Link Layer operates as expected, following the protocol Proximity-1 recommended standards. Each sublayer operates independently, with different processing times, although there is interoperability between sublayers (the output data of a Sublayer is the input of another). The Processing times of each sublayer vary greatly. The Physical Layer takes at least one hundred times longer than the Data Link Sublayers to conclude its processing, due to its more complex operations.

Regarding the acknowledgement process, there might be space to some improvements. The retransmission of PLCWs is an effortless improvement with a positive impact on the protocol results. A solution might be adding a variable to block the transmission of Sequence Controlled frames until a valid PLCW is received, or establishing an expectable receiving time, that if an acknowledgement is not received in that period of time, a PLCW must be retransmitted, before sending another Sequence Controlled frame. This enhances the FARM process.

For the different scenarios of a communication link (between orbiter, lander and rover) there are different attenuation factors affecting the transmission channel. From all the attenuation factors, the biggest contributor is the FSPL due to the big distance separating the two transceivers. Other factors that contribute to the attenuation of the transmitting signal are fading, Martian atmosphere, line of sight, Fresnel ellipsoid and the elevation angle. The medium loss through interplanetary space is ignored.

Regarding the demodulation, the preferable filter used is a fourth order Butterworth filter, due to the stopband and passband smoothness. The chosen fourth order was a compromise between sharpness and computational performance. The higher the order, the sharper the cut-off frequency. However, it takes a longer processing time to apply a higher order filter.

This protocol, however, has a drawback that has no avoidance. The FARM process requires an acknowledgment for Sequence Controlled frames, to ensure a good quality of service for that frame. Nonetheless, when it is necessary to retransmit a frame, due to an error in the transmission channel, the process of retransmitting the frame induces a delay, similar to the amount of time required to send a frame and to be received by the remote transceiver.

For future developments, one improvement in the protocol should be to have a frame header variable to identify not only the destination spacecraft ID, but a frame header section to identify the spacecraft ID source. This way, it allows operating in a multicast topology, addressing both source and destination nodes.

To sum up, this dissertation provides a scientific, technical and operational overview of the protocol Proximity-1, promoting future developments in space explorations. In addition, provides and makes it possible for smaller satellites to have a say in space communications. This dissertation confirmed the protocol standard recommendations is suitable for space explorations for short relay communications.

Overall, every work is incremental in the progress of science and technology. Rephrasing Neil Armstrong famous quote in 1969, this is one little step for mankind, but one giant leap in my personal career.

References

[1] CCSDS, *Proximity-1 Space Link Protocol – Rationale, Architecture and Scenarios*, Dec 2013, Informational report, CCSDS 210.0-G-2, Green Book, Washington DC, USA.

[2] CCSDS, *Proximity-1 Space Link Protocol – Data Link Layer*, Jul 2020, Recommended Standard, CCSDS 211.0-B-5, Blue Book, Washington DC, USA.

[3] CCSDS, *Proximity-1 Space Link Protocol – Physical Layer*, Dec 2013, Recommended Standard, CCSDS 211.1-B-4, Blue Book, Washington DC, USA.

[4] CCSDS, *Proximity-1 Space Link Protocol – Coding and Synchronization Sublayer*, October 2019, Recommended Standard, CCSDS 211.2-B-2, Blue Book, Washington DC, USA.

[5] Eliasson, Malin and Hassel, Johan 2015. *Architecture and Performance Evaluation of the Space Communication Protocol Proximity-1.* Master of Science Thesis in Embedded Eletronic System Design. Chalmers University of Technology, University of Gothenburg, Sweden.

[6] Tofigh, Ehsan. 2016. *Design and Implementation of High Performance BPSK Demodulator for Orbiter Communications*. Master of Science Thesis in Aerospace Engineering. Delft University of Technology, Delft, Netherlands.

[7] Matias, André. 2014. *Módulo de Comunicações Digitais para o ISTnanosat.* Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal.

[8] *TM Synchronization and Channel Coding*. Issue2. Recommendation for Space Data System Standards (Blue Book), CCSDS 131.0-B-2. Washington, D.C.:CCSDS, August 2011.

[9] G.A. Leonov. 2006. *Phase Synchronization: Theory and Applications*. St. Petersburg State University, Russia.

[10] Barat, Aakriti. 2017. *Analysis and Design of Phase Locked Loops with insight into Wavelet Analysis.* Ohio State University, United States of America.

[11] K.Borre.2007. *A software-Defined GPS and Galileo Receiver*: *A single-Frequency Approach. Applied and Numerical Harmonic Analysis*. Birkhuser, Basel.

[12] M. K. Simon and S. Million. 1996. *Residual Versus Suppressed-Carrier Coherent Communications*.

[13] Manique, Inês. 2015. *Cálculo da Atenuação numa Ligação Rádio Via-Ionosfera*. Instituto Superior Técnico, Lisboa, Portugal.

[14] Mars Reconnaissance Orbiter, National Aeronautics and Space Administration [Online]. Available: https://mars.nasa.gov/files/mro/MRO-060303.pdf. [Accessed July 2020].

[15] Haslett, Christopher. 2008. *Essentials of radio wave propagation*, pp 118–120. Cambridge University Press.

[16] *Propagation Issues for Communication between Earth and Mars*, NASA Jet Propulsion Laboratory, Deep Space Communications and Navigation Center of Excellence [Online]. Available: https://descanso.jpl.nasa.gov/propagation/mars/MarsPub_sec7.pdf. [Accessed August 2020]]

[17] *Microrover Radios and Antennas*, NASA Mars Exploration Program, Mars Pathfinder [Online]. Available: https://mars.nasa.gov/MPF/rovercom/itworks.html.

[18] Maral, Gérard and Bousquet, Michel. 2009. *Satellite Communications Systems, Systems, Techniques and Technologies*. Wiley 5th edition. Toulouse, France.

[19] Capela, Carlos. 2012. “*Protocol of Communications for VORSAT Satellite*”. Faculdade de Engenharia da Universidade do Porto, Portugal. Available: https://paginas.fe.up.pt/~ee97054/Transmission%20Losses.pdf.

[20] Recommendation ITU Radiocommunication Assembly, ITU-R SF.358-5. [Online] Available: https://www.itu.int/dms_pubrec/itu-r/rec/sf/R-REC-SF.358-5-199510-W!!PDF-E.pdf.

[21] Satellite Communications, Delta University. Egypt. [Online] Available: https://deltauniv.edu.eg/new/engineering/wp-content/uploads/Sat52015.pdf

[22] Ludwig, Roger and Taylor, Jim. March 2002. “*Voyager Telecommunications - Design and Performance Summary Series Article 4”*. NASA Jet Propulsion Laboratory, Deep Space Communications and Navigation Center of Excellence [Online]. Available: https://descanso.jpl.nasa.gov/DPSummary/Descanso4--Voyager_new.pdf.

[23] Salema, Carlos. *Feixes Hertzianos*. 2002. IST Press.

[24] Balanis, Constantine A. *Antenna Theory: Analysis and Design*, 4th Edition. 2016 John Wiley.

[25] Hall, Barclay. Propagation of Radiowaves. Hewitt 1988 IEE Press.

[26] A 48/56/64 kbit/s Data Circuit-Terminating Equipment Standardized for Use on Digital Point-to-Point Leased Circuits. ITU-T Recommendation V.38. Geneva: ITU, 1996.

[27] Performance Characteristics for Intermediate Data Rate Digital Carriers Using Convolutional Encoding/Viterbi Encoding. Rev. 10. IESS 308. Washington, DC: INTELSAT, 2000.

[28] Stanford Computer Science Department. [Online] Available: https://www.scs.stanford.edu/09au-cs144/notes/l11.pdf

[29] Signal Processing. StackExchange. IIR filters. [Online] Available: https://dsp.stackexchange.com/questions/9745/which-iir-filters-approximate-a-gaussian-filter.

[30] CCSDS, *Unified Space Data Link Protocol*, Oct 2018, Recommended Standard CCSDS 732.1-B-1, Blue Book, Washington DC, USA.

Annex A - Directives

(Source: Reference [2] Annex B)

This annex A is part of CCSDS, *Proximity-1 Space Link Protocol – Data Link Layer.*
Annex A is part of this dissertation annexes, in case the reader wants to consult quickly without having to go to annex B of reference [2].

A.1. SET TRANSMITTER PARAMETERS

The SET TRANSMITTER PARAMETERS directive shall consist of six fields, positioned contiguously in the following sequence (described from least significant bit, Bit 15, to most significant bit, Bit 0): Directive Type (3 bits), Transmitter Frequency (3 bits), Transmitter Data Encoding (2 bits), Transmitter Modulation (1 bit), Transmitter Data Rate (4 bits), Transmitter (TX) Mode (3 bits).

Table A.1.1 – SET TRANSMITTER PARAMETERS Directive

Bit 0 Bit 15

TX Mode 3 bits	TX Data Rate 4 bits	TX Modulation 1 bit	TX Data Encoding 2 bits	TX Frequency 3 bits	Directive Type 3 bits
0,1,2	3,4,5,6	7	8,9	10,11,12	13,14,15

The 3-bit Directive Type field identifies the type of protocol control directive and shall contain the binary value ‘000’ for the SET TRANSMITTER PARAMETERS directive.

The transmitter frequency 3 previous bits shall be used to set the transmitter frequency of the partnered transceiver to the desired value.

The return transmitter frequency (e.g., Orbiter as Initiator; Landed Asset as Responder), in the context of the forward link, this 3-bit field shall define the transmit frequency of the responder. Actual frequency assignments are given in Table *A.1.2.*

Table A.1.2 – Frequency assignments

‘000’	‘001’	‘010’	‘011’	‘100’	‘101’	‘110’	‘111’
Ch0R	Ch1R	Ch2R	Ch3R	Ch4R	Ch5R	Ch6R	Ch7R

Transmitter Data Encoding represent the following:

‘00’ = LDPC (2048,1024) rate ½ code;

‘01’ = Convolutional Code (7,1/2) (G2 vector inverted) with attached CRC-32;

‘10’ = Bypass all codes;

‘11’ = Concatenated (R-S(204,188), CC(7,1/2) Codes.

R-S(204,188) with CC(7,1/2) code is an ETSI standard. This option is not required for cross support.

Bit 7 of the SET TRANSMITTER PARAMETERS directive contains the transmission modulation options. ‘0’ corresponds to a Coherent frequency PSK or ‘1’ to a Non-coherent frequency PSK.

Bits 3 to 6 of the SET TRANSMITTER PARAMETERS directive contains the transmission data rates prior to encoding. Because of the NASA Mars Surveyor Project 2001 Odyssey implementation, there is an added constraint on the use of the values in the Data Rate field for 8, 32, 128, 256 kb/s. Data rate selection is linked to the modulation field value. NC indicates non-coherent PSK, and C indicates coherent PSK. R1 through R4 indicate the field is reserved for future definition by CCSDS. 1, 512, 1024, and 2048 kb/s data rates can only be selected using the SET PL EXTENSIONS directive.

Table A.1.3 – Encoding pattern ordered by data rate

‘1000’	‘1001’	‘0000’	‘0001’	‘1100’	‘0010’	‘0011’	‘1101’	‘0100’	‘0101’	‘0110’	‘0111’	‘1010’	‘1011’	‘1110’	‘1111’
2	4	8 NC	8 C	16	32 NC	32 C	64	128 NC	128 C	256 NC	256 C	R1	R2	R3	R4

Table A.1.4 - Encoding pattern ordered by bit pattern

‘0000’	‘0001’	‘0010’	‘0011’	‘0100’	‘0101’	‘0110’	‘0111’	‘1000’	‘1001’	‘1010’	‘1011’	‘1100’	‘1101’	‘1110’	‘1111’
8 NC	8 C	32 NC	32 C	128 NC	128 C	256 NC	256 C	2	4	R1	R2	16	64	R3	R4

Table A.1.5 – Proximity-1 coded data rates

Prox-1 Coded Symbol Rates (R_{cs})	Prox-1 Uncoded Data Rates (R_d) $R_d = R_{cs}$	Prox-1 Convolutionally Coded Data Rates (R_d) $R_d = .5 * R_{cs}$	Prox-1 LDPC computed data rates (R_d) $R_d = .48484 * R_{cs}$
1000	1000	N/A	N/A
2000	2000	1000	969.6969697
4000	4000	2000	1939.393939
8000	8000	4000	3878.787879
16000	16000	8000	7757.575758
32000	32000	16000	15515.15152
64000	64000	32000	31030.30303
128000	128000	64000	62060.60606
256000	256000	128000	124121.2121
512000	512000	256000	248242.4242
1024000	1024000	512000	496484.8485
2048000	2048000	1024000	992969.697
4096000	N/A	2048000	1985939.394

Bits 0 to 2 of the SET TRANSMITTER PARAMETERS directive contain the transmitter mode options, identifies the operating mode of the transmitter:

a) ‘000’ = Mission Specific;
b) ‘001’ = Proximity-1 Protocol;
c) ‘010’ = Mission Specific;
d) ‘011’ = Mission Specific;
e) ‘100’ = Mission Specific;
f) ‘101’ = Mission Specific;

g) ‘110’ = Reserved by CCSDS;

h) ‘111’ = Reserved by CCSDS

A.2. SET RECEIVER PARAMETERS DIRECTIVE

The SET RECEIVER PARAMETERS directive consists of six fields, positioned contiguously in the following sequence (from least significant bit, bit 15, to most significant bit, bit 0) presented in Table *A.3.1*.

Table A.2.1 – SET RECEIVER PARAMETERS Directive

Bit 0 Bit 15

RX Mode 3 bits	RX Rate 4 bits	RX Modulation 1 bit	RX Data Decoding 2 bits	RX Frequency 3 bits	Directive Type 3 bits
0,1,2	3,4,5,6	7	8,9	10,11,12	13,14,15

Bits 13 to 15 identifies the type of protocol control directive and contain the binary value ‘010’ for the SET PARAMETERS directive.

Bits 10 to 12 set the receiver frequency of the partnered transceiver to the desired value. In the context of the forward link, this 3-bit field define the receive frequency of the responder. Actual frequency assignments are given in the Physical Layer (see Table *A.1.2*).

Bits 8 and 9 contain the following coding options:

a) ‘00’ = LDPC (2048,1024) rate ½ code;

b) ‘01’ = Convolutional Code (7, ½) (G2 vector inverted) with attached CRC-32;

c) ‘10’ = Bypass all codes;

d) ‘11’ = Concatenated R-S (204,188), CC (7,1/2).

R-S (204,188) with CC(7,1/2) code is an ETSI standard. This option is not required for cross support. (See reference [H1] from reference [2] for more details).

Bit 7 refers to Coherent frequency PSK (‘0’) or Non-coherent frequency PSK (‘1’).

Bits 3 to 6 contain one of the receiver data rates (see Table *A.1.5*).

Bits 0 to 2 contain the receiver mode options.

a) ‘000’ = Mission Specific;

b) ‘001’ = Proximity-1 Protocol;

c) ‘010’ = Mission Specific;

d) ‘011’ = Mission Specific;

e) ‘100’ = Mission Specific;

f) ‘101’ = Mission Specific;

g) ‘110’ = Reserved by CCSDS;

h) ‘111’ = Reserved by CCSDS;

A.3. SET PL EXTENSIONS

The Set PL Extensions directive is the mechanism by which additional Physical Layer parameters can be enabled or disabled. This directive is transferred across the Proximity link from the local transceiver to the remote transceiver. This directive consists of ten fields described in Table *A.3.1*.

Table A.3.1 – SET PL EXTENSIONS

Bit 0 Bit 15

Direction	Freq Table	Rate Table	Carrier MOD	Data MOD	Mode Select	Scrambler	Differential Mark Encoding	R-S Code	Directive Type
1 bit	1 bit	1 bit	2 bits	2 bits	2 bits	2 bits	1 bit	1 bit	3 bits
(0)	(1)	(2)	(3,4)	(5,6)	(7,8)	(9,10)	(11)	(12)	13,14,15

Bits 13 to 15 contain the binary value ‘110’ (directive type).

Bit 12 indicates which R-S Code is used. ‘0’ corresponds to R-S(204,188) code and ‘1’ to R-S(255,239) code.

Bit 11 indicates whether Differential Mark Encoding is enabled. ‘0’ corresponds to no differential encoding, while ‘1’ corresponds to differential encoding enabled. The current data bit is exclusive ORed with the previously transmitted bit to determine the value of the current transmitted bit. When the current data bit is ‘1’, then the current encoder output level changes relative to the previous output value. If the data bit is a ‘0’ then the current encoder output bit level remains constant relative to the previous output value.

Bits 9 and 10 indicate if and what type of digital bit scrambling is used.

a) ‘00’ = Bypass all bit scrambling;
b) ‘01’ = CCITT bit scrambling enabled (reference [26]);
c) ‘10’ = Bypass all bit scrambling;
d) ‘11’ = IESS bit scrambling enabled (reference [27])

Bits 7 and 8 indicate the type of carrier suppression used:

a) ‘00’ = Suppressed Carrier (requires transmit side utilize Modulation Index of 90º and transmit/receive sides utilize Differential Mark Encoding/Decoding;
b) ‘01’ = Residual Carrier;
c) ‘10’ = Reserved;
d) ‘11’ = Reserved;

Bits 5 and 6 indicate the type of data modulation used:

a) ‘00’ = NRZ-L;
b) ‘01’ = Bi-Phase-Level (Manchester);
c) ‘10’ = Reserved;
d) ‘11’ = Reserved.

Bits 3 and 4 indicate the type of carrier modulation to be used:

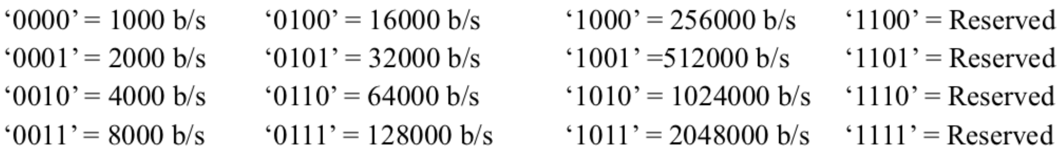
a) ‘00’ = No modulation;
b) ‘01’ = PSK;

c) ‘10’ = FSK;

d) ‘11’ = QPSK.

(Note: Options c) and d) are not required for cross-support)

Bit 2 indicate which set of data rates prior to encoding shall be used. ‘0’ corresponds to default set defined in the Data Rate Field of the SET TRANSMITTER PARAMETERS and SET RECEIVER PARAMETERS Directives. ‘1’ corresponds to the extended physical layer data rate defined below:



‘0000’ = 1000 b/s
‘0001’ = 2000 b/s
‘0010’ = 4000 b/s
‘0011’ = 8000 b/s
‘0100’ = 16000 b/s
‘0101’ = 32000 b/s
‘0110’ = 64000 b/s
‘0111’ = 128000 b/s
‘1000’ = 256000 b/s
‘1001’ =512000 b/s
‘1010’ = 1024000 b/s
‘1011’ = 2048000 b/s
‘1100’ = Reserved
‘1101’ = Reserved
‘1110’ = Reserved
‘1111’ = Reserved

(Option a) is required for cross-support. Option b) is required for cross-support for data rates less than 2000b/s and greater than 256 000 b/s.

Bit 1 indicates what set of frequencies is to be used. ‘0’ for channels 0-7 defined in the frequency field of the SET TRANSMITTER PARAMETERS and SET RECEIVER PARAMETERS Directives and specifically in the Proximity-1 Physical Layer. ‘1’ for channels 8-15 defined in the Extended Physical Layer Frequency Set (see Table *A.1.2*).

Bit 0 indicates if the fields in this directive apply to the transmitting or receiving side of the transceiver. ‘0’ corresponds to the transmit side, while ‘1’ corresponds to the receive side.

Annex B – Cyclic Redundancy Check

(Source: Reference [4] Annex C)

This annex B is part of CCSDS, *Proximity-1 Space Link Protocol – Coding and Synchronization Sublayer.* Annex B is part of this dissertation annexes, in case the reader wants to consult quickly without having to go to annex C of reference [4].

B.1. Encoding Procedures

The encoding procedure shall accept an (n-32) bit Version-3 Transfer Frame and generate a systematic binary (n, n-32) block code by appending a 32-bit Cyclic Redundancy Check (CRC-32) as the final 32 bits of the PLTU. The ASM is not used in the encoding procedure.

If M(*X*) is the (n-32)-bit information message to be encoded expressed as a polynomial with binary coefficients, with the first bit transferred being the most significant bit M0 taken as the coefficient of the highest power of X, then the Equation for the 32-bit Cyclic Redundancy Check, expressed as a polynomial R(X) with binary coefficients, shall be:

R(X)=[X^32 . M(X)] moduloG(X)

Where G(X) is the generating polynomial given by:

G(X) = X^32 + X^23 + X^21 + X^11 + X^2 + 1

And where the first transferred bit of the Cyclic Redundancy Check is the most significant bit R0 taken as the coefficient of the highest power of X.

The n-bit CRC-32 encoded block, expressed as a polynomial C(X) with binary coefficients, shall be:

C(X)=X^32 – M(X) + R(X)

The (n-32) bits of the message are input in the order M0, …,Mn-33, and the n bits of the codeword are output in the order C0, … ,Cn-1 = M0, … , Mn-33, R0, …, R31.

B.2. Decoding Procedures

The decoding procedure shall accept an n-bit received codeword, including the 32-bit Cyclic Redundancy Check, and generates a 32-bit syndrome. An error is detected if and only if at least one of the syndrome bits is non-zero.

The received block C*(X) shall equal the transmitted codeword C(X) plus (modulo two) the n-bit error block E(X), C*(X) = C(X) + E(X), where both are expressed as polynomials of the same form, i.e., with the most significant bit C0 or E0 taken as the binary coefficient of the highest power of X.

With C*(X) being the n-bit received codeword with the first transferred bit being the most significant bit C0* taken as the coefficient of the highest power of X, then the Equation for the 32-bit syndrome, expressed as a polynomial S(X) with binary coefficients, shall be:

S(X)= [X^32 . C*(X)] modulo G(X)

The syndrome polynomial will be ‘zero’ if no error is detected, and non-zero if an error is detected, with the most significant bit S0 taken as the coefficient of the highest power of X.

Annex C – Proximity Link Control Word

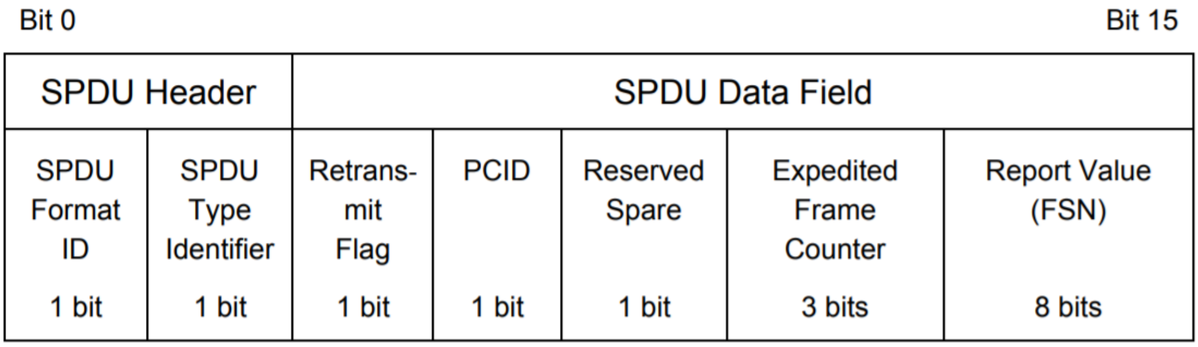
(Source: Reference [2] Annex F4.4)

This annex C is part of this dissertation annexes, in case the reader wants to consult quickly without having to go to annex F4.4 of reference [2]. This annex C is part of CCSDS, *Proximity-1 Space Link Protocol – Data Link Layer.*

The PLCW consists of seven fields positioned contiguously, and described from least (Bit 15) to most significant bit (Bit 0) in the following sequence:

The PLCW is transmitted using the Expedited QoS.

Table C.1. - Proximity link control word fields. (Source: reference [2], annex F4.4)



Bit 0 Bit 15

SPDU Header		SPDU Data Field				
SPDU Format ID	SPDU Type Identifier	Retrans-mit Flag	PCID	Reserved Spare	Expedited Frame Counter	Report Value (FSN)
1 bit	1 bit	1 bit	1 bit	1 bit	3 bits	8 bits

Bits 8–15 of the PLCW contain the Report Value that correspond to the next Sequence Controlled Frame Sequence. Separate Report Values are maintained for each PCID independent of the I/O port.

Bits 5–7 of the PLCW contain the Expedited Frame Counter that provides a modulo-8 counter indicating that Expedited frames have been received. This value is set to ‘all zero’, indicating that it is not used.

Bit 4 of the PLCW contains a Reserved Spare bit, which is set to ‘0’.

Bit 3 of the PLCW contains the Physical Channel Identification with which this report is associated. The PCID field is set to ‘0’. Each PCID in use has its own PLCW reporting activated.

Bit 2 of the PLCW contains the PLCW Retransmit Flag that is always ‘0’. A lack of increment in the Report Value indicates that a received frame failed a frame acceptance check and that a retransmission of the expected frame is required.

Bit 1 of the PLCW contains the SPDU Type Identifier that identifies SPDU type as a PLCW and contains the binary value ‘0’.

Bit 0 of the PLCW contains the SPDU Format ID that indicates that the length of the SPDU is fixed and contains the binary value ‘1’.

Annex D – Throughput Efficiency

This annex is a quote of reference [1] pages 4-37, 4-38 and 4-39. It was not mentioned in the dissertation because the MATLAB simulation did not account on dividing a frame into smaller frames, nor accommodate many frames into one message (SPDU). However, this Protocol has that possibility, so, this annex points out one aspect that should be taken into account on future developments, in order to make the data throughput more efficient.

“On a bidirectional link, 100-percent throughput efficiency degrades when the fastest link has sent all of its data (within the window size) while the slow link completes sending a U-frame before it sends the acknowledging PLCW (one PLCW can acknowledge a window length of frames). During this time, the fastest link starts progressively retransmitting the data from the Sent queue, since the window size has been reached. In order to maintain 100-percent throughput on the fastest link and minimize the non-progression of this link, the user frame size on the slowest link needs to be reduced (see Figure *D.1*).

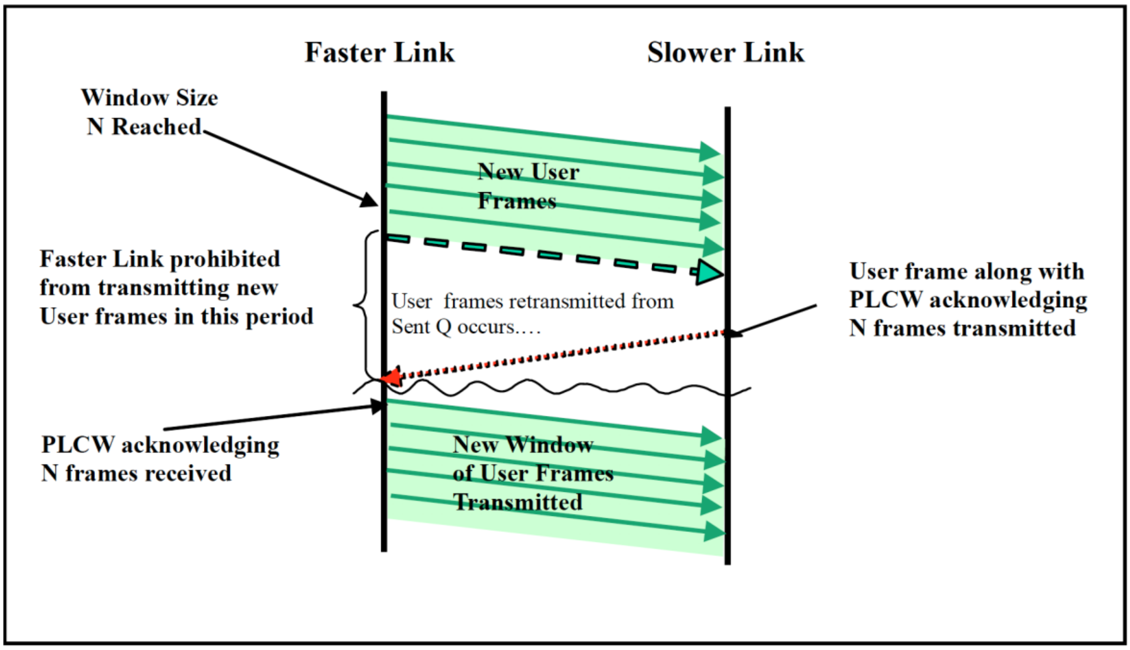


Figure D.1*.* – Loss of 100-percent throughput on the faster link of a bidirectional Link.

Figure *D.2* shows that by reducing the frame size on the link with the slowest data rate, 100-percent data throughput is maintained on both links even as the fastest link achieves the highest Proximity-1 data rate. This assumes a window size (N) of 127, which is the maximum allowed in Proximity-1. In Figure *D.3*, showing the extreme case of N=1, it can be seen that the ability to maintain 100-percent data throughput at a data rate ratio of 1:32 is lost. This result in the faster side of the link is spending more time progressively retransmitting frames. This loss of throughput is proportional to the data rate ratio, slower link to faster link rate. The higher this ratio, the longer the faster link fails to make progress in transmitting new user frames. For completeness, Figure *D.4* shows N=32 and the loss of data throughput of 100 percent at a data rate ratio of 1:512. The data rate ratio at which there is loss of data throughput of 100 percent is proportional to the transmission window size. So the bigger the window size, the larger the data rate ratio can be before losing data throughput of 100 percent.” (Reference [1], pages 4-37, 4-38 and 4-39)

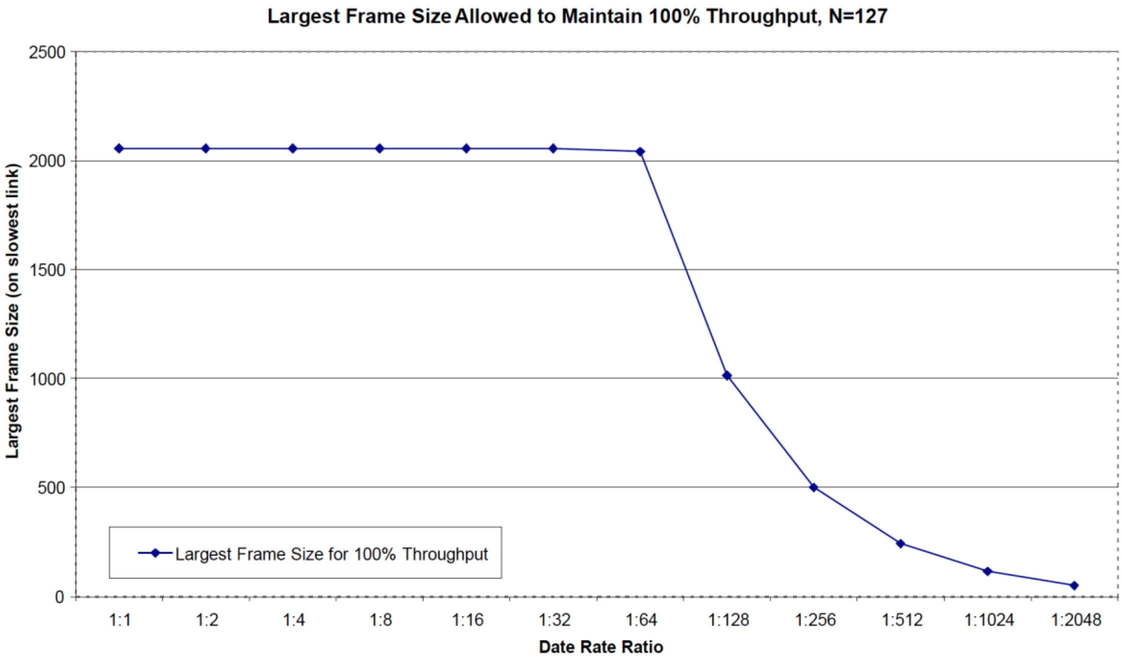


Figure D.2. – Largest frame size (octets) on slowest link allowed maintaining 100-Percent throughput (N=127)

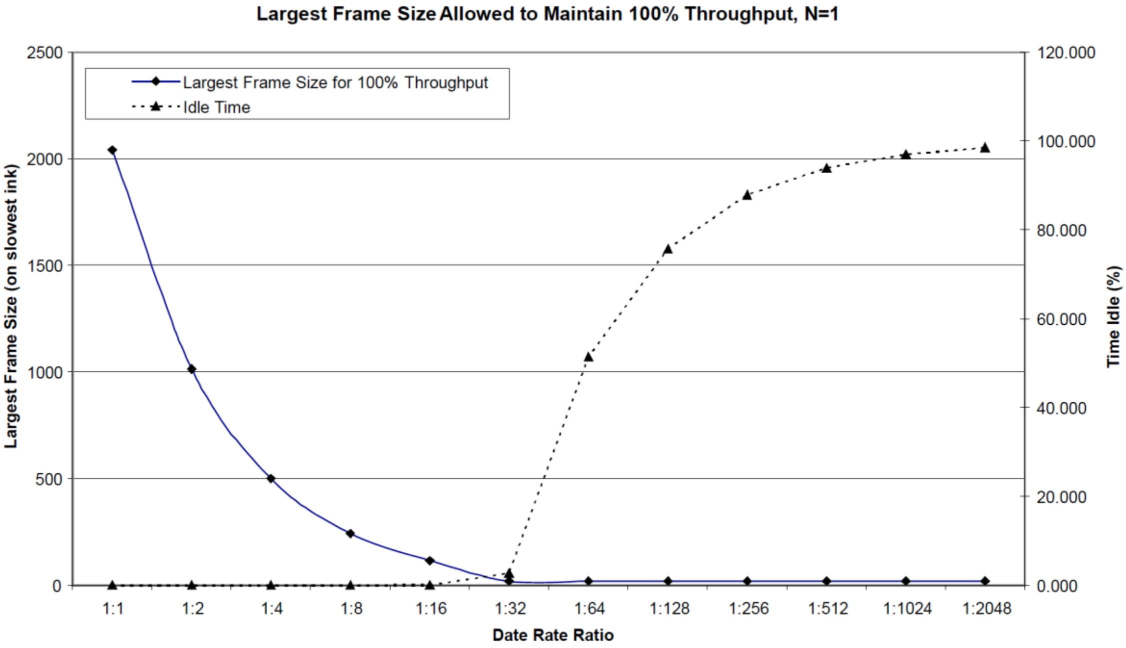


Figure D.3. – Largest frame size (octets) on slowest link allowed maintaining 100-Percent throughput (N=1)

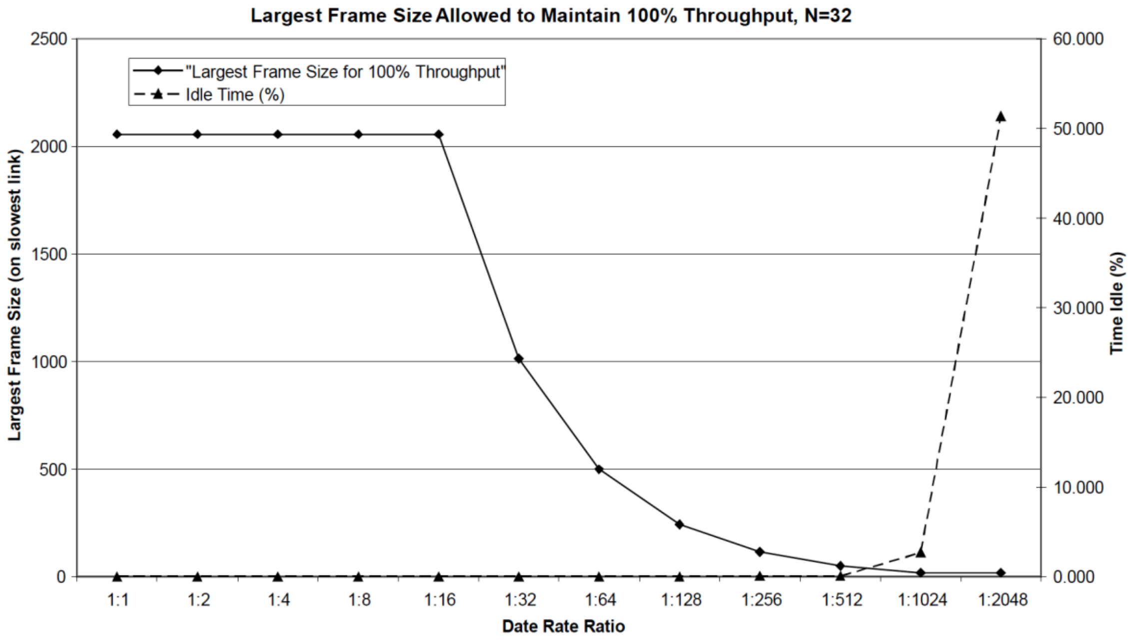


Figure D.4. – Largest frame size (octets) on the slowest link allowed maintaining 100-Percent throughput (N=32)

Annex E – Simulator Global Structure

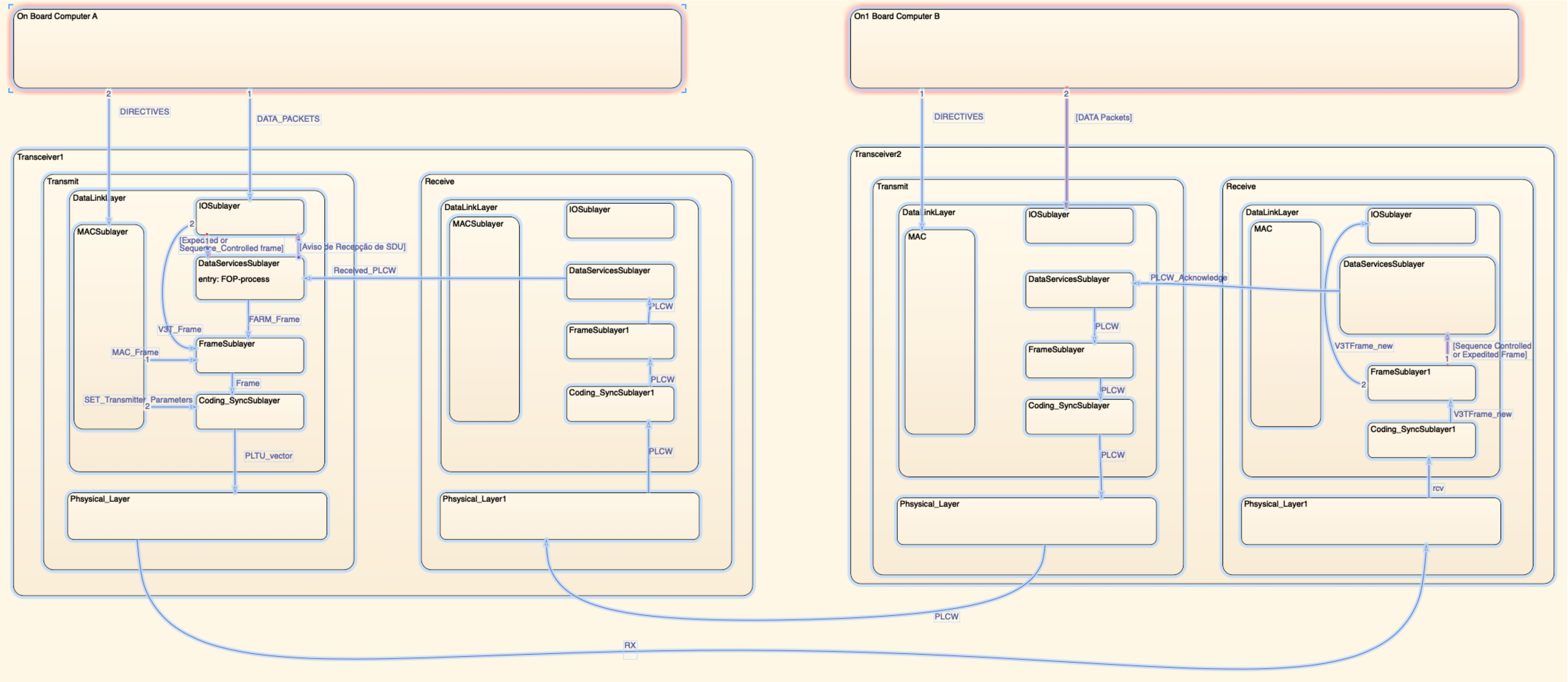


Figure E.1. – Global structure of *Transceiver A* and *Transceiver B*

Annex F – Demonstration of the signal amplitude vs number of samples

$$\mathrm{y} = \frac{1}{N}\sum_{i=1}^{N} x_i \quad , \qquad \mathrm{x}_i \ \text{v.a. iid } \mathrm{N}(\mathrm{m}_x, \sigma_x{}^2)^{[1]} \tag{5.16}$$

$$\begin{aligned} \mathrm{m}_y &= E[y] \\ &= E\left[\frac{1}{N}\sum_{i=1}^{N} x_i\right] \\ &= \frac{1}{N}.\sum_{i=1}^{N} E[x_i] \\ &= \frac{1}{N}.N.m_x \\ &= m_x \end{aligned} \tag{5.17}$$

$$\begin{aligned} \sigma_y{}^2 &= E\left[\left(y - m_y\right)^2\right] \\ &= E\left[y^2 - 2ym_y + m_y{}^2\right] \\ &= E[y^2] - 2m_y E[y] + m_y{}^2 \\ &= E[y^2] - m_y{}^2 \end{aligned} \tag{5.18}$$

$$\begin{aligned} E[y^2] &= E\left[\frac{1}{N}\sum_{i=1}^{N} x_i \ .\frac{1}{N}\sum_{j=1}^{N} x_j\right] \\ &= \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N} E[x_i x_j] \\ &= \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N} E[x_i x_j] \\ &= \frac{1}{N^2}\sum_{i=1}^{N}\left[\sum_{\substack{i=1 \\ j\neq i}}^{N} E[x_i x_j] + E[x_i{}^2]\right] \\ &= \frac{1}{N^2}\sum_{i=1}^{N}[\ (\mathrm{N}-1).\mathrm{m}_x{}^2 + \sigma_x{}^2 + m_x{}^2] \end{aligned} \tag{5.19}$$

Considering that $[x_i].E\left[x_j\right] = m_x{}^2$; $E[x_i{}^2] = \sigma_x{}^2 + m_x{}^2$; and that $\sum_{\substack{i=1 \\ j\neq i}}^{N} E[x_i x_j]$ is true for N-1 cases, while $E[x_i{}^2]$ only happens once, it is possible to simplify to:

---

[1] **v.a** = random variable; **i.i.d**. = independent and equally distributed.

$$E[y^2] = \frac{1}{N^2} \sum_{i=1}^{N} [\,\mathrm{N}.\mathrm{m}_x{}^2 + \sigma_x{}^2] \tag{5.20}$$

$$= \frac{1}{N^2}\left[\,\mathrm{N}^2.\mathrm{m}_x{}^2 + N.\sigma_x{}^2\right]$$

$$= \mathrm{m}_x{}^2 + \frac{\sigma_x{}^2}{N}$$

Joining Equations *5.18* and *5.20*,

$$\sigma_y{}^2 = E[y^2] - m_y{}^2 \tag{5.18}$$

$$E[y^2] = m_X{}^2 + \frac{\sigma_x{}^2}{N} \tag{5.20}$$

and knowing that $m_y{}^2 = m_x{}^2$, it is possible to conclude that:

$$\sigma_y{}^2 = \mathrm{m}_x{}^2 + \frac{\sigma_x{}^2}{N} - m_y{}^2 \tag{5.21}$$

$$= \mathrm{m}_x{}^2 + \frac{\sigma_x{}^2}{N} - m_x{}^2$$

$$\sigma_y{}^2 = \frac{\sigma_x{}^2}{N}$$

Annex G – Received Signal Using Low Pass Butterworth Filters

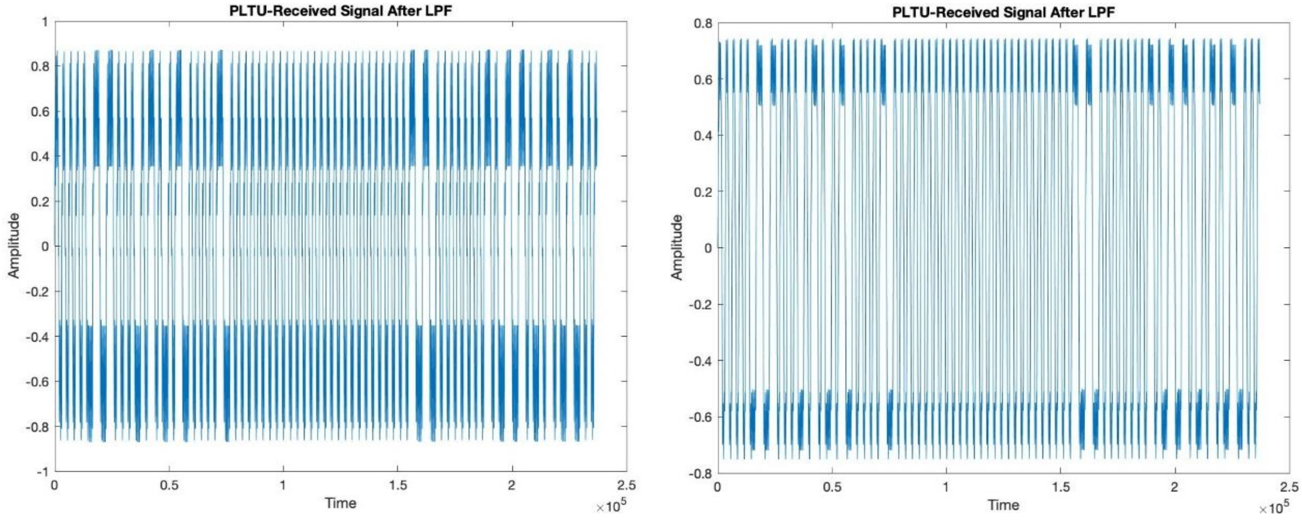


Figure G. 1 – Received signal after a Low Pass 1st and 2nd order Butterworth filter, respectively.

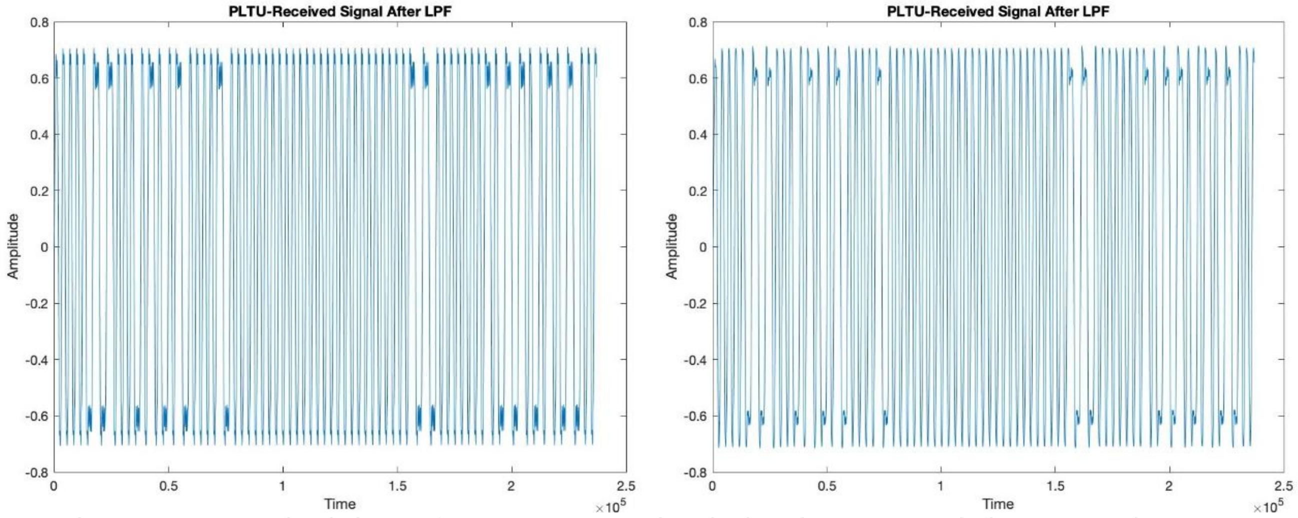


Figure G. 2 – Received signal after a Low Pass 3rd and 4th order Butterworth filter, respectively.

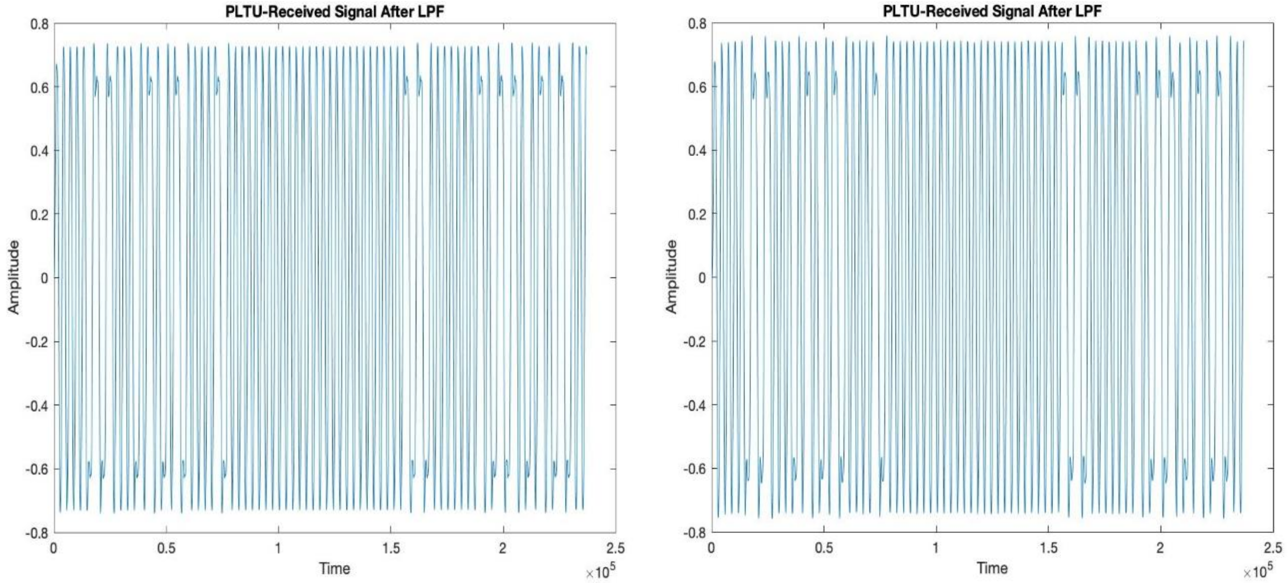


Figure G. 3 – Received signal after a Low Pass 5th and 6th order Butterworth filter, respectively.

Annex H – Received Signal Using Low Pass Chebyshev Type 1 Filters

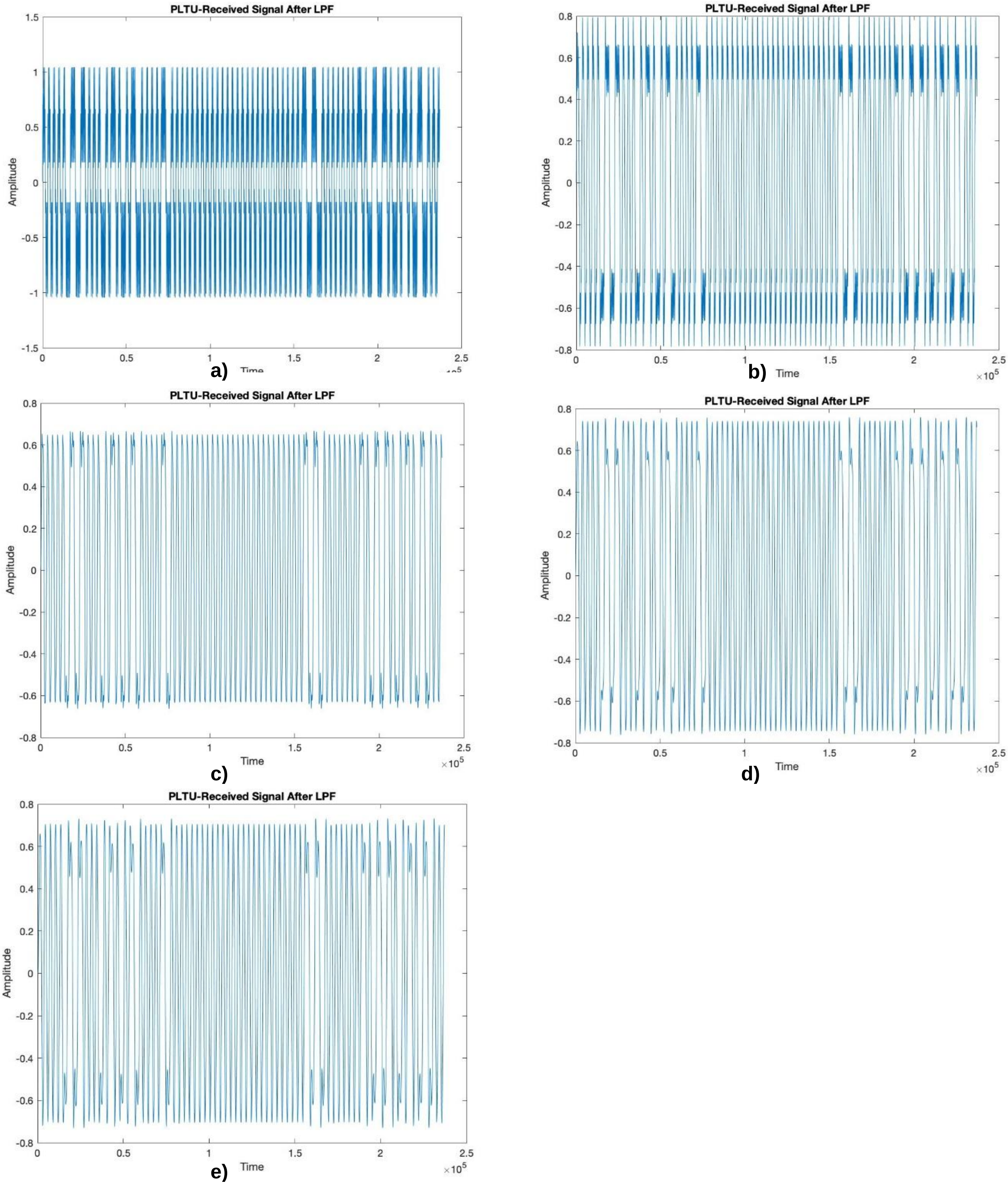


Figure H. 1 – Received signals after a Low Pass Chebyshev filter:

a) 1st order; **b)** 2nd order; **c)** 3rd order; **d)** 4th order; **e)** 5th order.

Annex I – Received Signal using Low Pass Eliptic Filters

The Low Pass Elliptic filter is applied and Figure *I.1* represents its effects on the received signal.

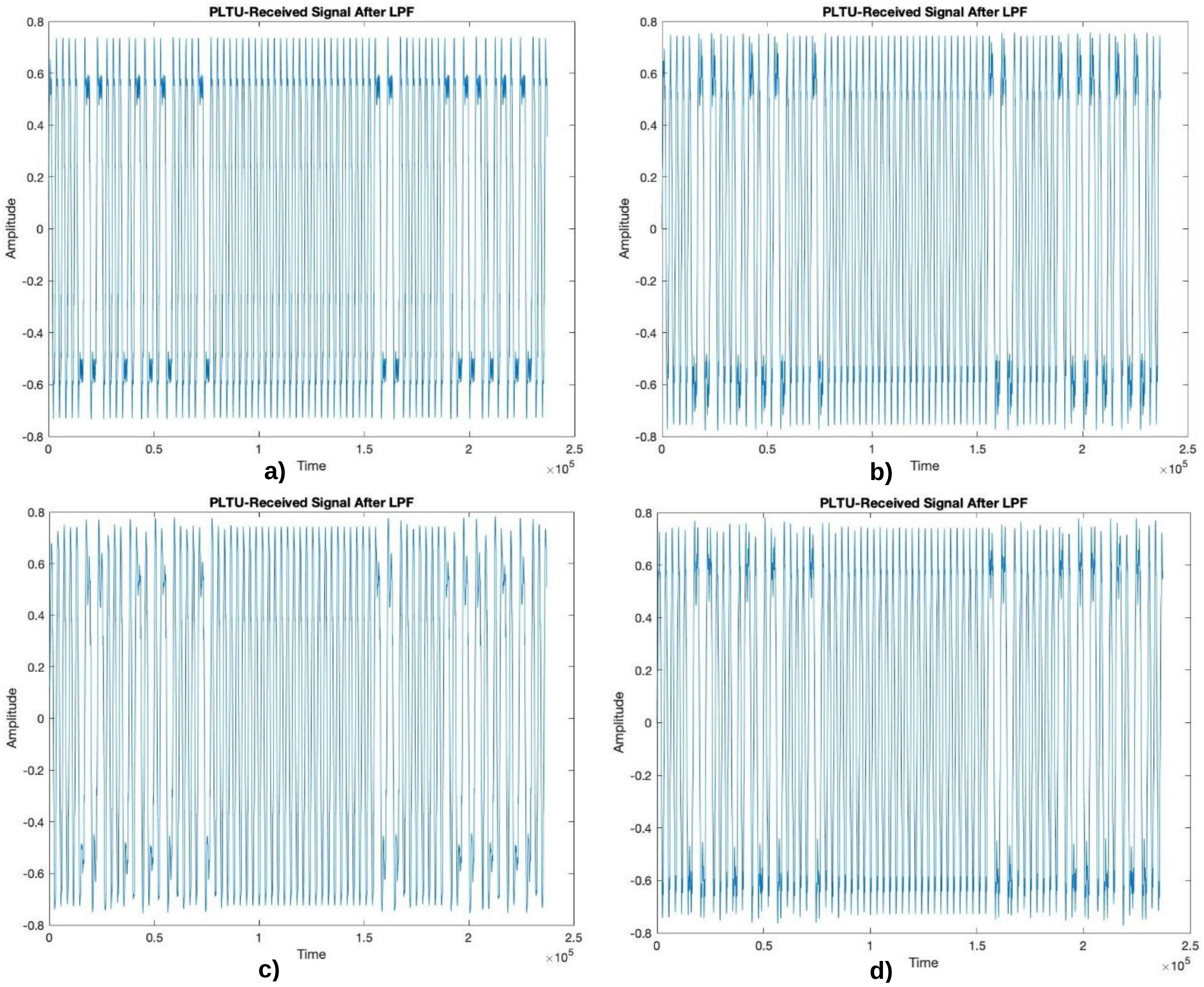
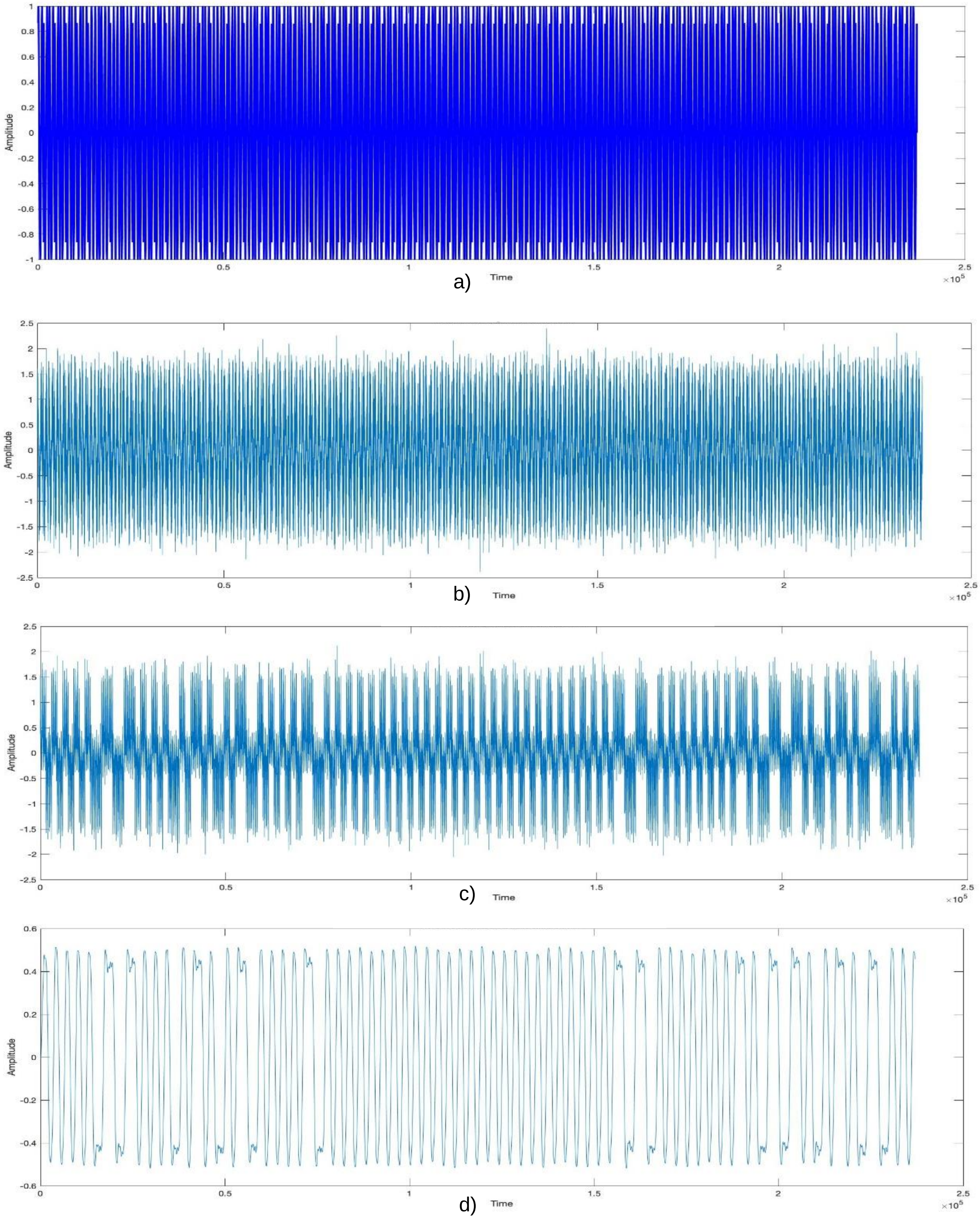


Figure I. 1 – Received signals after a Low Pass Elliptic filters:

a) 2nd order; **b)** 3rd order; **c)** 4th order; **d)** 5th order.

Annex J – Transmission Power

For Pt=0.5 W and a SNR=10 dB:



a)

b)

c)

d)

Figure J. 1 – **a)** Transmitted modulated signal; **b)** Transmitted modulated signal with noise; **c)** Received signal before Low Pass filter; **d)** Received signal after a Low Pass filter.

For Pt=1 W and SNR=10 dB:

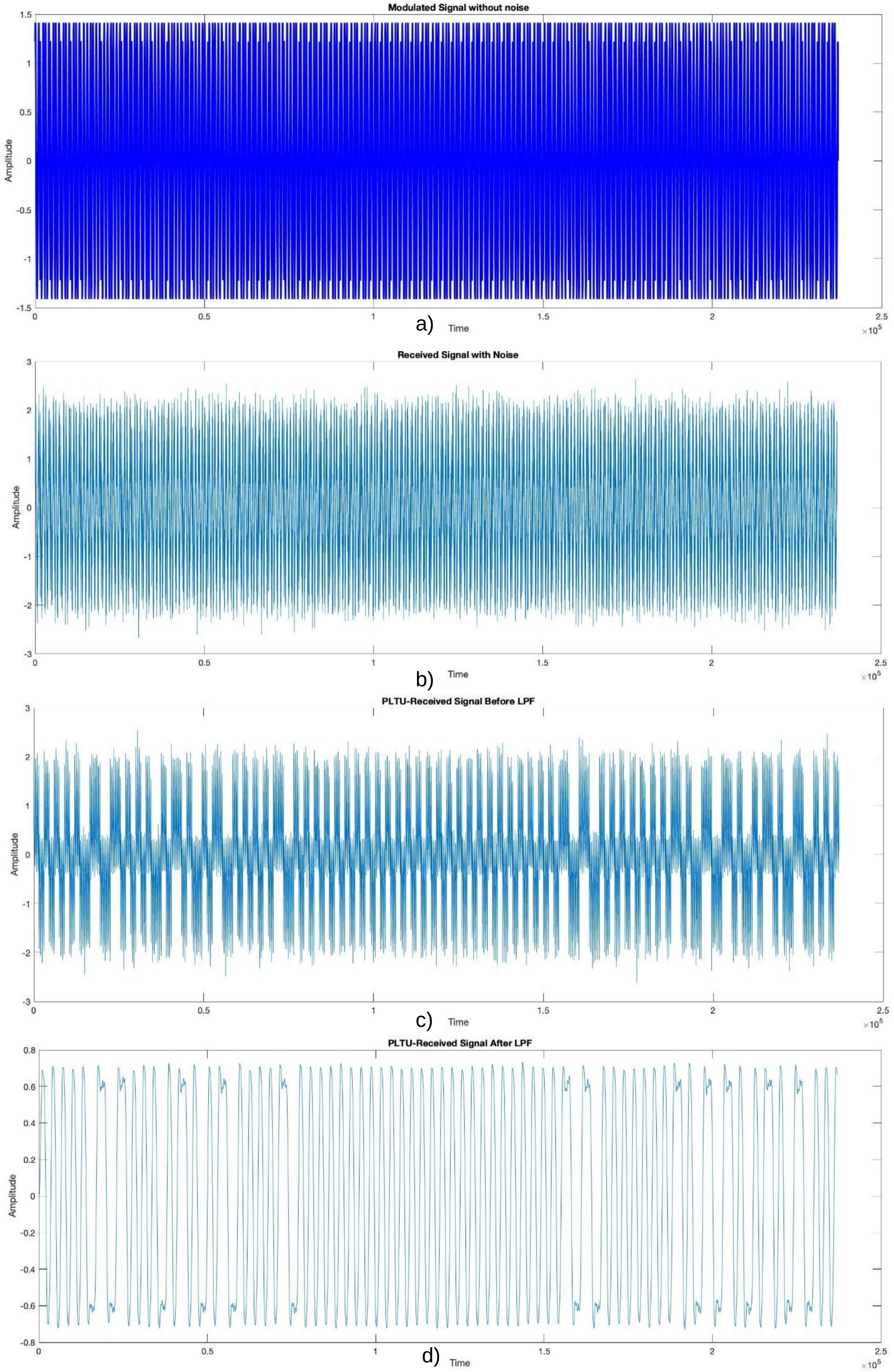


Figure J. 2 – **a)** Transmitted modulated signal; **b)** Transmitted modulated signal with noise; **c)** Received signal before Low Pass filter; **d)** Received Signal after a Low Pass filter.

For Pt=10 W and SNR=10 dB:

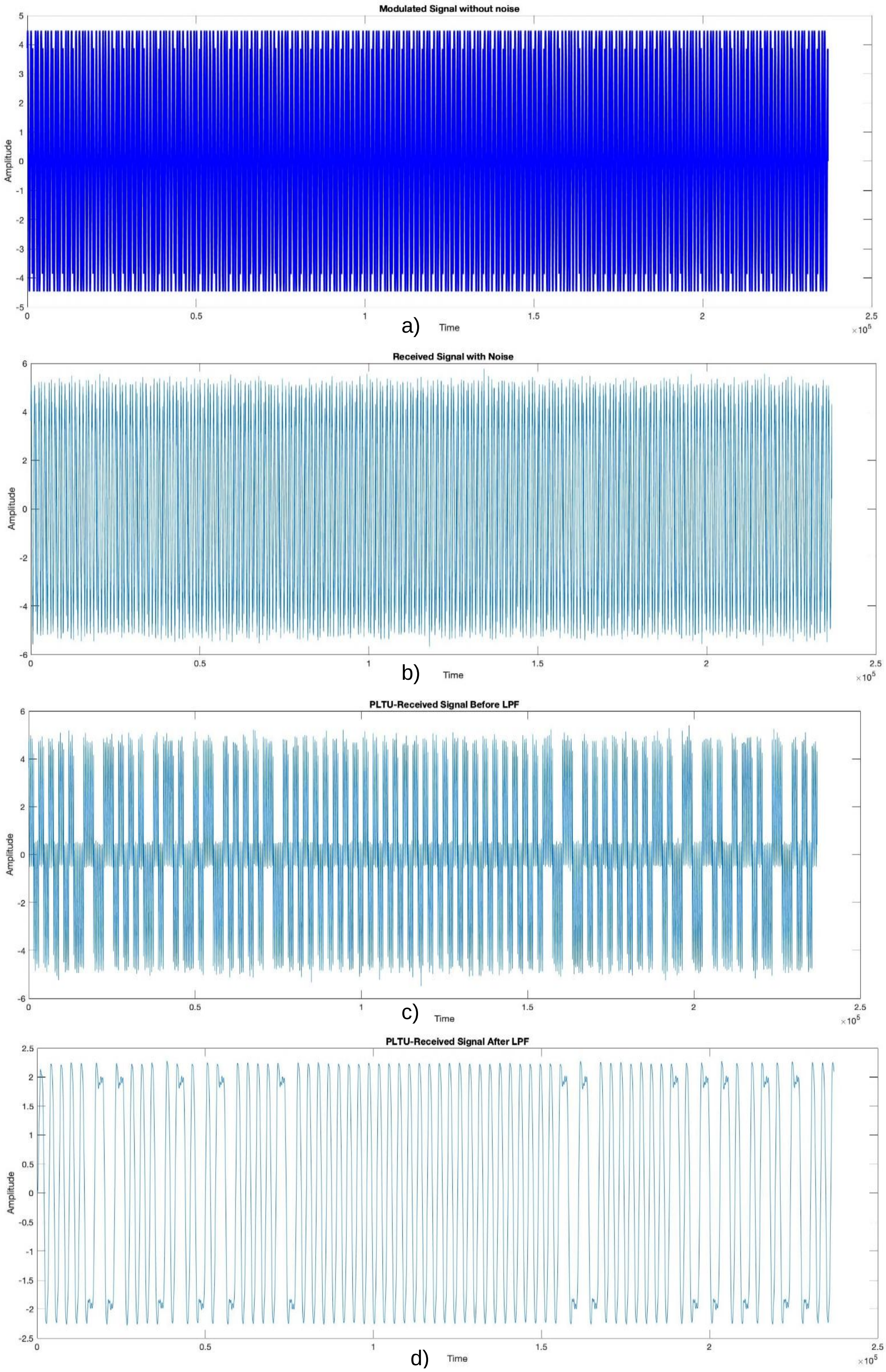


Figure J. 3 – **a)** Transmitted modulated signal; **b)** Transmitted modulated signal with noise; **c)** Received signal before Low Pass filter; **d)** Received signal after a Low Pass filter.

Annex K – Signal to Noise Ratio Variations

For Pt=1 and SNR = -3 dB:

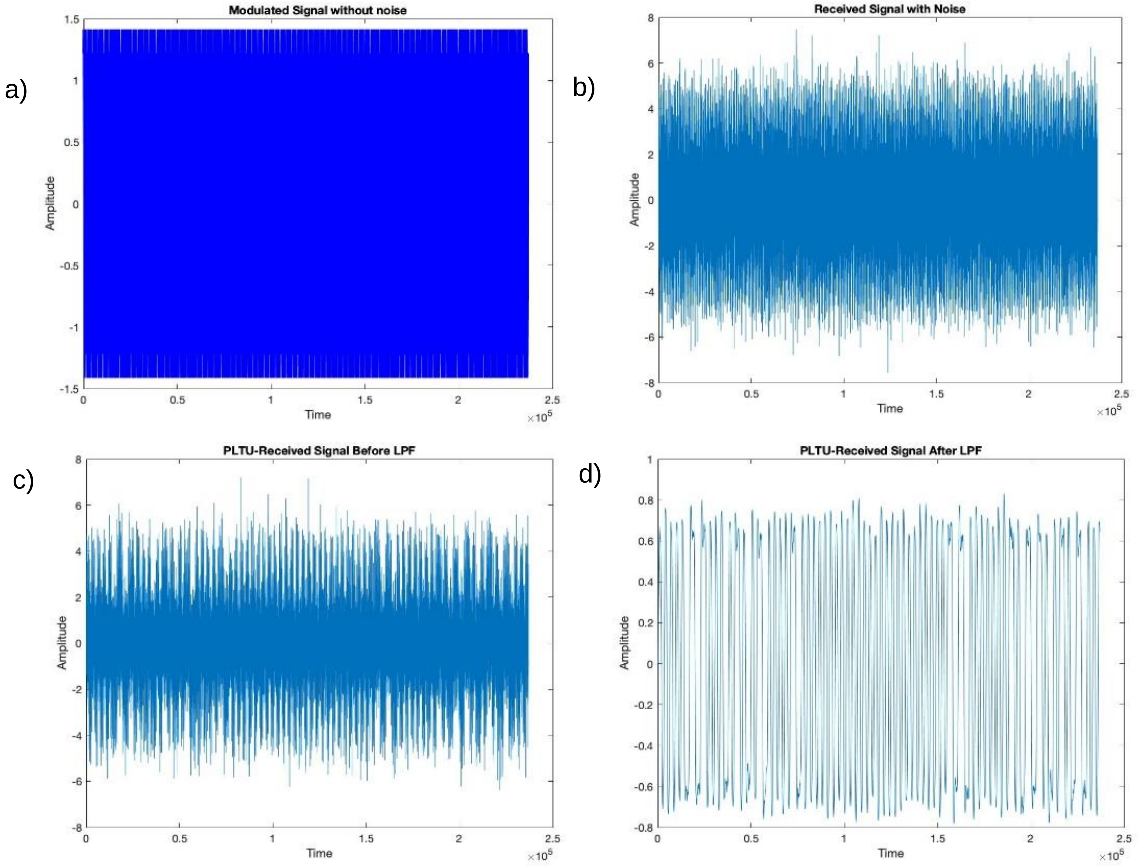


Figure K. 1 – **a)** Transmitted modulated signal; **b)** Transmitted modulated signal with noise; **c)** Received signal before Low Pass filter; **d)** Received signal after a Low Pass filter.

For Pt=1 W and SNR = 0 dB (the transmitted signal has the same power as the noise):

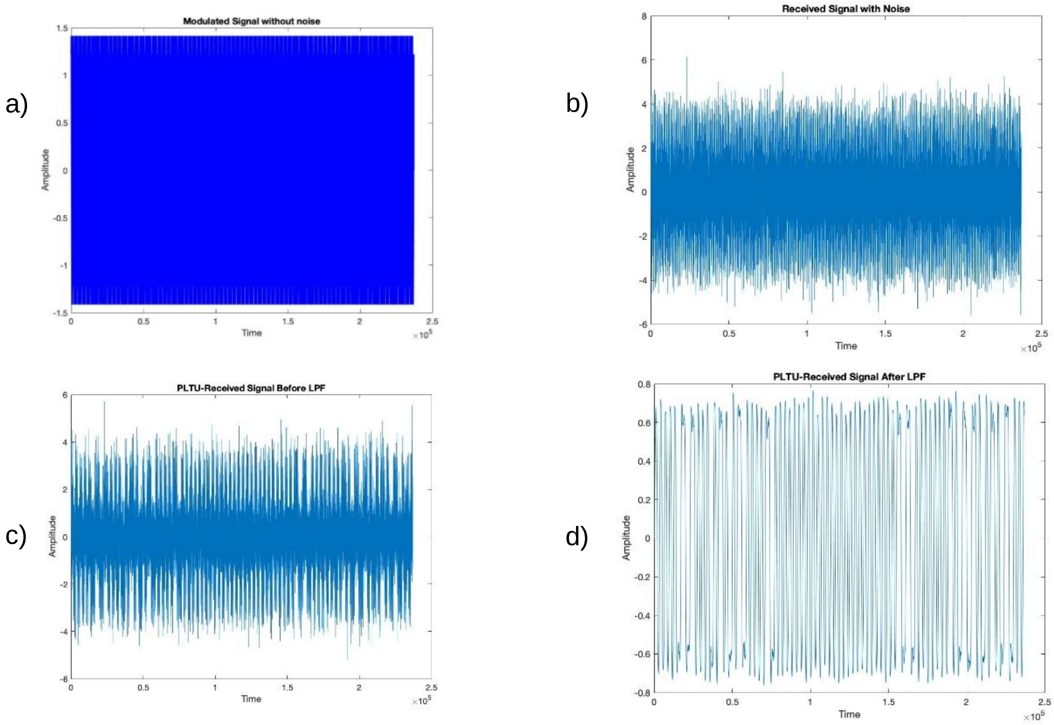


Figure K. 2 – **a)** Transmitted modulated signal; **b)** Transmitted modulated signal with noise; **c)** Received signal before Low Pass filter; **d)** Received signal after a Low Pass filter.

For Pt=1 and SNR = 3 dB:

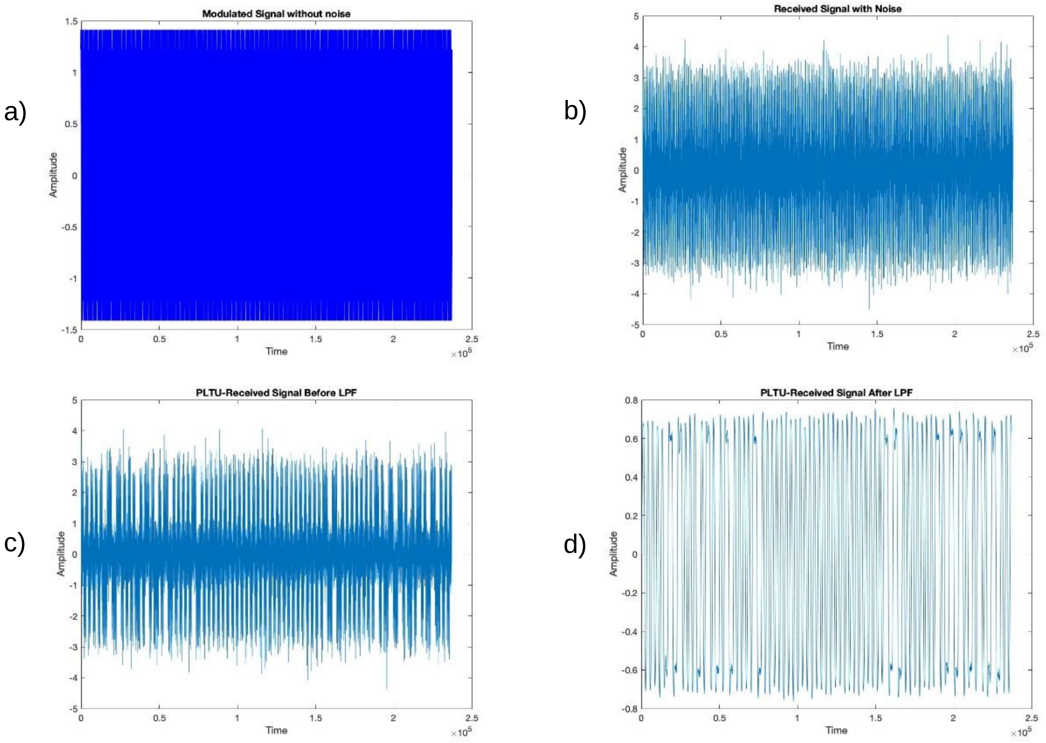


Figure K. 3 – **a)** Transmitted modulated signal; **b)** Transmitted modulated signal with noise; **c)** Received signal before Low Pass filter; **d)** Received signal after a Low Pass filter.

For Pt=1 and SNR=10 dB (signal is ten times stronger than the noise power):

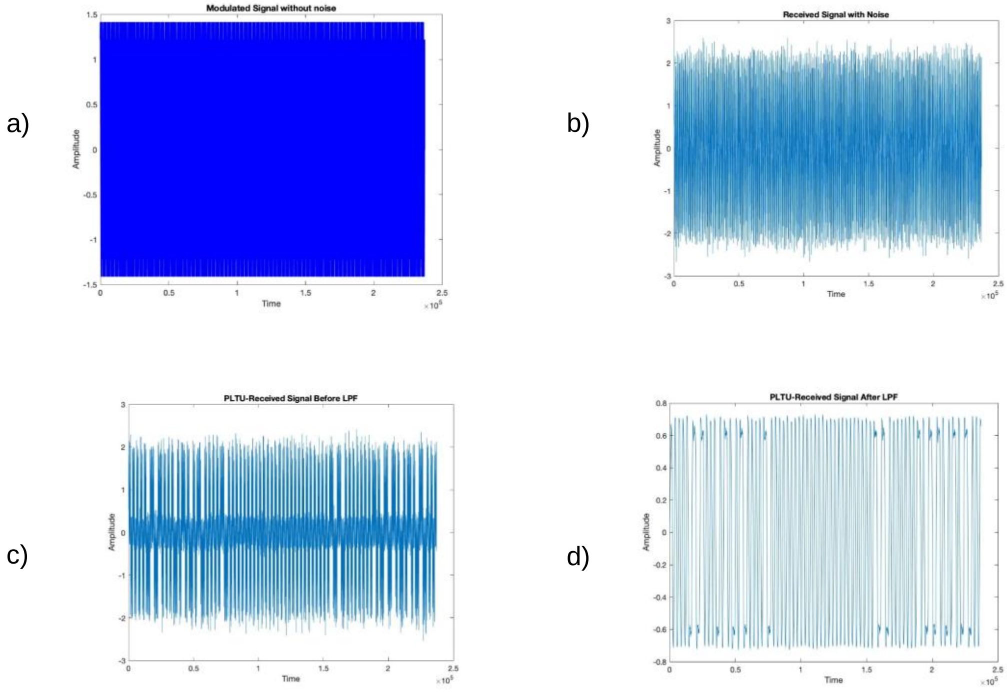


Figure K. 4 – **a)** Transmitted modulated signal; **b)** Transmitted modulated signal with noise; **c)** Received signal before Low Pass filter; **d)** Received signal after a Low Pass filter.

For Pt=1 and SNR=50 dB (signal is one hundred thousand times more powerful than the noise):

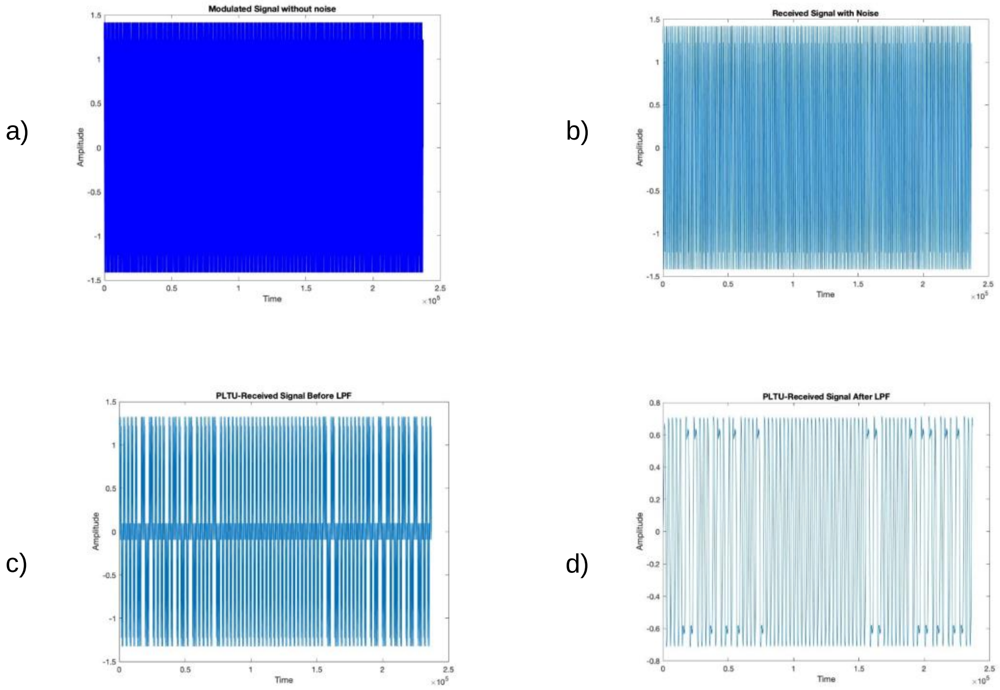


Figure K. 5 – **a)** Transmitted modulated signal; **b)** Transmitted modulated signal with noise; **c)** Received signal before Low Pass filter; **d)** Received signal after a Low Pass filter.