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Mobile network for space telecommunications

5G network on the lunar surface

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Abstract

During the current decade, the focus of space research and exploration is represented by the return of the human being to the Moon, with the aim of establishing a continuous and sustainable presence on its surface. One of the key aspects for the creation of a lunar outpost is the management of communications and services related to them.

The objective of this study, performed in collaboration with TIM S.p.A. and the Polytechnic of Turin, is to carry out an evaluation on the possible use of mobile networks in the space sector. The ability to provide the services and performance currently achieved by terrestrial networks and technology is critical to the conquest of the lunar environment, now, and other celestial bodies, in the future.

To achieve this goal, the state of the art of communications in the space field was evaluated and the history of mobile networks was retraced, focusing on the capabilities currently developed by the fifth generation. Subsequently, space programs, past and currently underway, which have glimpsed the potential in the application of the mobile network to extraterrestrial scenarios were investigated. Following a well-defined logical path, the possible realization of a lunar surface network was evaluated, proposing the use of the currently available technology, and evaluating the arrangement of the equipment to obtain a result adequate to expectations.

The results show how it is possible to use communication tools currently in use on Earth for the construction of a lunar network, adapting the equipment to the space environment and arranging them according to the limits dictated by the morphology of the selected lunar area.

Future research may investigate the optimization of the possible distribution of cells depending on the exact location of the lunar village proposed by the Artemis program.

Acknowledgements

Before the work is presented, I want to dedicate a few words to all the people who have made it possible to achieve this goal by contributing with their experience, their support, and their affection.

Firstly, I would like to express my sincere gratitude to my supervisor prof. Giorgio Guglieri for allowing me to take part in this project and having once again guided me in the degree course. I will always carry his valuable advice and experience with me.

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To my parents, for having always been by my side during the period of my studies and for allowing me to live it with serenity and dedication.

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Acronyms

ABC
    Audio Bus Coupler

ACTRA
    Assembly/Contingency Transmitter Receiver Assembly

AGI
    Analytical Graphics Incorporation

ALINA
    Autonomous Landing and Navigation Module

ALQ
    Audi Lunar Quattro

AMPS
    Advanced Mobile Phone System

AoA
    Angle of Arrival

ATU
    Audio Terminal Units

AUAI
    Assembly-Contingency system /UHF Audio Interface

BSP
    Baseband Signal Processor

A17

Apollo 17

CDMA

Code Division Multiple Access (CDMA)

CLPS

Commercial Lunar Payloads Services

COTS

Commercial Off The Shelves

CSA

Canadian Space Agency

DAIU

Docked Audio Interface Unit

eMBB

Enhanced Mobile BroadBand

EMU

Extravehicular Mobile Unit

ESA

European Spatial Agency

EVA

Extra Vehicular Activity

FDMA

Frequency Division Multiple Access

GNSS

Global Navigation Satellite System

GPRS

General Packet Radio Service

GPS

Global Positioning System

GSM

Global System for Mobile communications

HALO

Habitation And Logistic Outpost

HEO

High Earth Orbit

HGA

High-Gain Antenna

HLCS

Halo Lunar Communication System

HLS

Human Landing System

HST

Hubble Space Telescope

I-HAB

International HABitat module

IAC

Internal Audio Controller

IAS

Internal Audio Subsystem

ICSSC

International Communications Satellite Systems Conference

IoT

Internet of Things

ISS

International Space Station

ITU

International Telecommunication Union

JAXA

Japanese Aerospace eXploration Agency

JPL

Jet Propulsion Laboratory

LADEE

Lunar Laser and Dust Environment Explorer

LEO

Low Earth Orbit

LGA

Low-Gain Antenna

LLGT

Lunar Laser Ground Terminal

LOP-G

Lunar Orbital Platform – Gateway

LRO

Lunar Reconnaissance Orbit

LTE

Long Term Evolution

LTV

Lunar Terrain Vehicle

MCS

Mission Critical Services

MEC

Multi-access Edge Computing

MIMO

Multiple Input Multiple Output

MMS

Multimedia Messaging Service

mMTC

massive Machine Type Communication

NASA

National Aeronautics and Space Administration

NMT

Nordic Mobile Telephone

NFV

Network Function Virtualization

NRHO

Near Rectilinear Halo Orbit

NTT

Nippon Telegraph and Telephone

PFM

Pulse Frequency Modulation

PNT

Positioning, Navigation and Timing

PPE

power and Propulsion Element

QoS

Quality of Signal

RFG

Radio Frequency Group

RKA

Roscosmos

ROS
: Russian Orbital Segment

SAR
: Search and Rescue

SCaN
: Space Communication and Navigation

SDN
: Software Defined Networking

SLS
: Space Launch System

SMS
: Short Message Service

SSCS
: Space-to-Space Communication System

STK
: System Tool Kit

TACS
: Total Access Communications System

TDRS
: Tracking and Data Relay Satellite

TLI
: Translunar Injection Maneuver

ToA
: Time of Arrival

UHF
: Ultra High Frequencies

UMTS
: Universal Mobile Telecommunication System

URLLC

Ultra Reliable – Low Latency Communication

USOS

United States Orbital Segment

VDS

Video Distribution System

VHF

Very High Frequency

VIPER

Volatile Investigating Polar Exploration Rover

Chapter 1

Introduction

Within this study, carried out in collaboration with TIM S.p.A., an analysis of the possibility of using mobile networks in space telecommunications will be presented. In particular, the use of the emerging 5G network to meet the new communication needs in the space field will be evaluated, due to the imminent return of the human being to the Moon in a stable plant, before embarking on the long journey towards the exploration of Mars and other planets in the Solar System.

In the coming years the increase in communication skills will turn out to be one of the pivotal points for the continuation of space activities and human exploration, which will take man further and further away from his mother planet. Faster and more efficient communication will not only serve to improve the transmission of mission data or to monitor the health of astronauts and space modules. The uncertainties related to the new environments to be explored will make it necessary to be able to remotely manage the research tools, but the most important factor will be represented by the human psyche. The increase in the distance of the objectives to be achieved will bring with it a considerable increase in mission times and the human emotional sphere could be affected by the lack of people we love. The increase in the performance of spatial communications will serve to bring the possibility of streaming video and making voice and video calls in real time even in the deepest space.

This study stems from the collaboration between the Polytechnic of Turin and TIM S.p.A., the national leader in the telecommunications sector. The project was born within the Italian company with the aim of exploring a new area in which to expand its business model. The use of mobile networks for space applications is not so easy to realize, but not even visionary, so the pursuit of this goal could bring visibility and new important collaborations.

The space sector is now at the dawn of the integration between these two worlds, so the choice to deepen this theme is dictated by its topicality and the hope is that this study can represent an important step for the dissemination of the knowledge acquired to date and the search for an applicable solution.

1.1 Thesis contribution

The goal of this thesis is to carry out a feasibility study for the use of 5G technology in space, highlighting the critical issues related to its use in a different and hostile environment, the strengths that would bring considerable advantages and some possible solutions of use.

The fundamental part for the success of this study was the bibliographic research carried out to collect information on the state of the art of space and terrestrial communications. As mentioned above, the use of the mobile network in space does not represent a utopia, indeed, some projects are currently underway or have already provided some initial indications. The next purpose was therefore to find those who have already exposed theories or evaluations about it and who intends in the coming years to test this technology on the Moon. Once this information was known, it was necessary to find a common thread and a logical sense that would allow to combine the results obtained from previous studies in a single document.

Finally, thanks to the collaboration of AGI – Analytical Graphics Inc. and the Italian reseller GMSpazio s.r.l. suppliers of a license for the STK – Systems Tool Kit software, it was possible to carry out some evaluations and simulations of the intended use scenarios.

1.2 Outline

The outline of the thesis is defined as follows.

Chapter 2 describes the key points of current space communications, before dwelling on the communication systems present on board the international space station, the only module in orbit continuously inhabited.

Chapter 3 shifts the focus on the state of the art of terrestrial mobile networks, retracing their history from the first to the fourth generation, before explaining the main features and innovations of the fifth generation of mobile network.

Chapter 4 opens with an overview of the needs and opportunities that led to the idea of coupling these two worlds, also collecting the problems and critical issues dictated by the space environment that will have to be studied and solved in order to make the most of efficient components but not designed to live an adventure in space. Subsequently, he dwells on past and currently ongoing programs that plan to study and take advantage of 4G / 5G technologies for telecommunications in space.

Chapter 5 presents in more detail what the possible application scenarios for this binomial will be.

Chapter 6 evaluates the logical process to be followed for the design of a 5G lunar surface network, attaching and combining the various results obtained from the studies carried out on the subject.

Chapter 7 presents the simulated scenarios thanks to the use of STK software, highlighting the proposed architecture, the hypotheses and the analyzes carried out.

In the final conclusions of this document, the results obtained regarding the possibility of integrating 5G technology in space communications will be discussed and further insights and ideas will be proposed to improve following feasibility studies on the subject.

Chapter 2

Space communications: state of the art

The second chapter of this study aims to present an analysis of the state of the art of space communications. This first activity is essential for the project "The Mobile Network for the telecommunication in space" carried out in collaboration with the Polytechnic of Turin and TIM S.p.A.

Figure 2.1. An artist's rendering of Tracking and Data Relay Satellites alongside two of the flagship missions they support, the International Space Station and the Hubble Space Telescope. Credits: NASA [1].

Communicating with space is not as simple as it may seems and doing it with excellent quality and minimum delay is an even more compelling challenge. Over the years NASA has accumulated experience and knowledge to transport data to and from space. The SCaN (Space Communication and Navigation) program allows this exchange of information, works to improve its quality and efficiency trying to study new solutions to overcome the challenges proposed by the space environment.

Starting from the basics, the communication link relies on the use of a transmitter and a receiver. The first encodes the message by turning it into an electromagnetic wave, whose properties are modulated to represent the necessary data. The wave travels through space before reaching the receiver where a demodulation of the signal allows the decoding of the data. It works according to the same principle as terrestrial communications, only at a very great distance. To be able to overcome this difficulty it was necessary to create a terrestrial network, including numerous antennas of different sizes and for different purposes, which can cover all seven continents. In addition to direct communications between the spacecraft and Earth, many NASA missions rely on the presence of relay satellites (TDRSS) that re-transmit the signal allowing communication beyond the line of sight. This architecture offers advantages in terms of availability of the communication link [19].

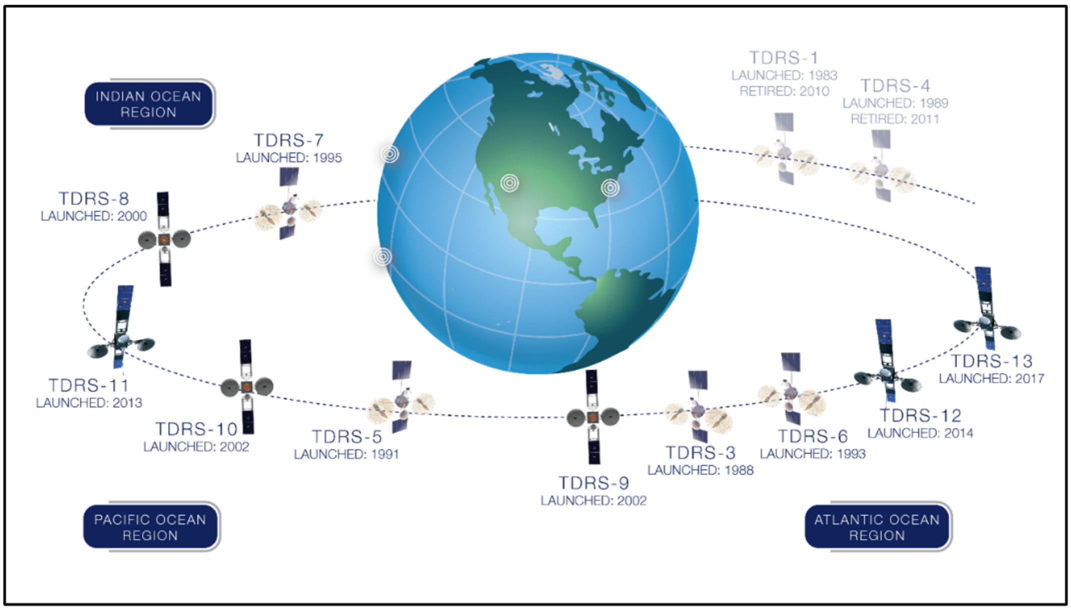

Figure 2.2. TDRS Constellation. Credits: NASA.

TDRS are placed in a geosynchronous orbit, where their orbital periods are equal to the Earth's sidereal day. Today's configuration has ten satellites in orbit deployed to provide continuous relay service to elements such as the Hubble Space Telescope (HST) or the ISS:

1. Four of first generation of TDRS.
2. Three of second generation of TDRS.
3. Three of third generation of TDRS.

The great distance brings with it two other factors to consider: the possible interference and the latency of the signal.

When waves travel long distances or through the atmosphere, the quality of the signal can deteriorate. Radiation from the Sun or other celestial bodies interferes with the signal, and in the absence of atmospheric and magnetic protection from the Earth the effect is amplified. To ensure accurate data is still received, NASA uses error detection and correction methods using algorithms capable of interpreting transmission noises. However, it is not the only problem related to the presence of radiation, if they damage the storage area used for the encryption key the communication will be interrupted, they are therefore one of the reasons why the exchange of information between the Earth and many spacecrafts takes place without encryption. The problem is not so serious for the transmission satellites through which the crew of the International Space Station connects, but this is not the case with most other spacecraft in Earth orbit. The lack of signal encryption is a sore point, spacecrafts and satellites can represent potential attack targets. ESA (European Spatial Agency) researchers are experimenting with two solutions for maintaining encrypted communication with satellites while containing costs:

1. A spare secondary key attached to the hardware. If the primary key is compromised, the system will generate a new key based on the secondary key. However, only a limited number of keys can be created.
2. Several identical microprocessors core. If one core goes out of order, another can intervene at any time while the defective core restores its configuration and repairs itself.

To test these solutions, a device was shipped to the ISS in April 2019 and a test phase lasting at least one year is expected.

In addition to this, communication does not occur instantaneously, electromagnetic waves propagate with the speed of light. For a spacecraft in orbit near the Earth the time elapsed is almost negligible, but for distant bodies it can become a great challenge. To communicate with an astronaut on Mars it will be necessary to wait from four to twenty-four minutes for the signal to transmit, depending on the relative position between the two planets. To communicate with an astronaut on the Moon will take about three seconds between round trip of the signal. Another important aspect concerns the characteristics of the signal. The choice of the frequency band used, and its amplitude impacts on the ability to transmit data. Higher bandwidths allow more data to be carried per second, ensuring spacecrafts down link data faster. To this day, NASA has always made use of radio wave-based communications. However, in its history the ISS has also functioned as a research and development hub and in recent years has been working on the development of a communication system based on infrared lasers. This new type of optical communication will offer space missions even higher data rates for data transmission. To maximize the data rate bandwidth is not the only factor to consider, communications engineers operate a trade off also evaluating the transmission distance, the size of the antennas and the powers available at both ends.

2.1 ISS-International Space Station

Figure 2.3. International Space Station, ISS. Credits: NASA.

The analysis takes as a reference point the telecommunications systems currently in use on the International Space Station, simply called the ISS, because it is the only continuously inhabited orbiting module. Its in orbit construction began on November 20, 1998, when the Zarya module was launched from the Baikonur Cosmodrome in Kazakhstan. ISS is in Low Earth Orbit (LEO), maintained at an altitude between 330 and 410 km above sea level. Traveling at an average speed of 27600 km/h it manages to make about 15.5 daily orbits. The project is jointly managed by five space agencies: NASA (United States of America), RKA (Russia), ESA (Europe Union), JAXA (Japan), CSA (Canada). Its main task is to develop and test new technologies of interest in the field of space exploration, study the keeping alive of a crew on missions outside of Earth orbit and gain experience for long-duration space travel. In addition, the laboratories on board allow to carry out chemical, physical, medical, biological and life experiments in an environment of micro gravity. Since November 2, 2000, the date on which the first crew occupied the station, it has been continuously inhabited by astronauts from NASA and other international space organizations who live and work on board. Among their main needs there is to constantly communicate with the Earth, both for professional and recreational activities [2].

In this regard, the ISS is equipped with different communication systems, each used by entities and for fixed purposes. The two main segments present are the Russian Orbital Segment (ROS) and the US Orbital System (USOS).

2.1.1 ROS-Russian Orbital Segment

The Russian segment communicates using three different systems, with equipment separate from those in use on the U.S. segment:

1. directly with the Earth using the LIRA antenna.
2. through the LUCH Data Relay Satellite System.
3. Using the Voskhod-M communication system.

LIRA antenna is mounted on the Zvezda service module (DOS – 8), the third module launched during the construction of the ISS, as well as the central module of the Russian competence section. The same antenna also allows the connection with the LUCH Data Relay Satellite System, a constellation of three satellites in Geostationary orbit capable of two-way communications with ISS, Soyuz modules and satellites in LEO orbit to allow you to stay in contact with the Mission Control Center, its coverage is only equal to 50% of the orbit made by the ISS.

The Voskhod – M system has a dual function. It allows telephone communication between the Russian modules of the ISS and the US modules, communication with the Earth segment for the transmission of telemetry data (VHF – 1) and space-to-space communications with Orbiter or during EVA (VHF – 2) through the antennas mounted on the Zvezda module.

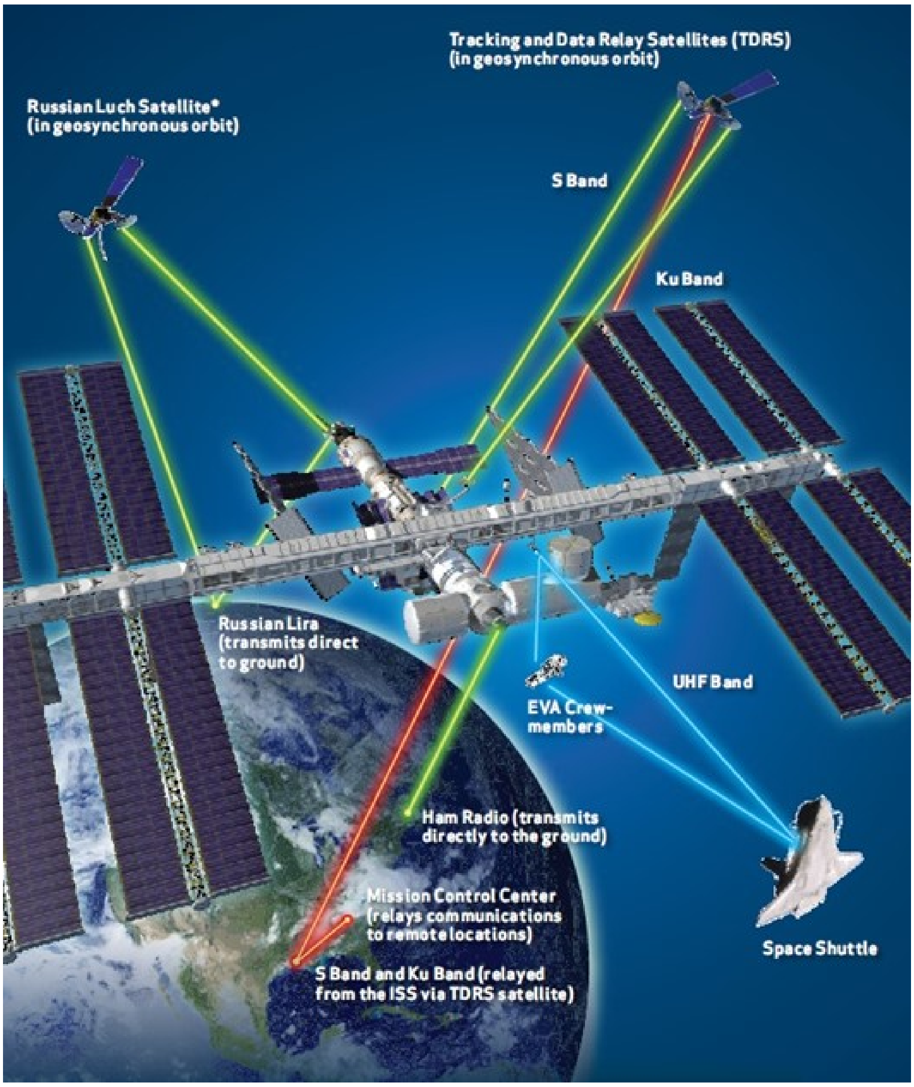

Figure 2.4. ISS Communications architecture. Credits: NASA.

2.1.2 USOS-US Orbital Segment

The communication network that keeps astronauts in touch with the U.S. Mission Control Center is based on the use of ground antennas (Ground – Based Antennas) and a constellation of satellites (TDRSS – Tracking and Data Relay Satellite System) that together make up the "Space Network" managed by NASA.

The placement of the TDRS satellites in geosynchronous orbit allows continuous communication with the International Satellite Station which will always see at least one satellite from every possible expected position in space. In fact, this

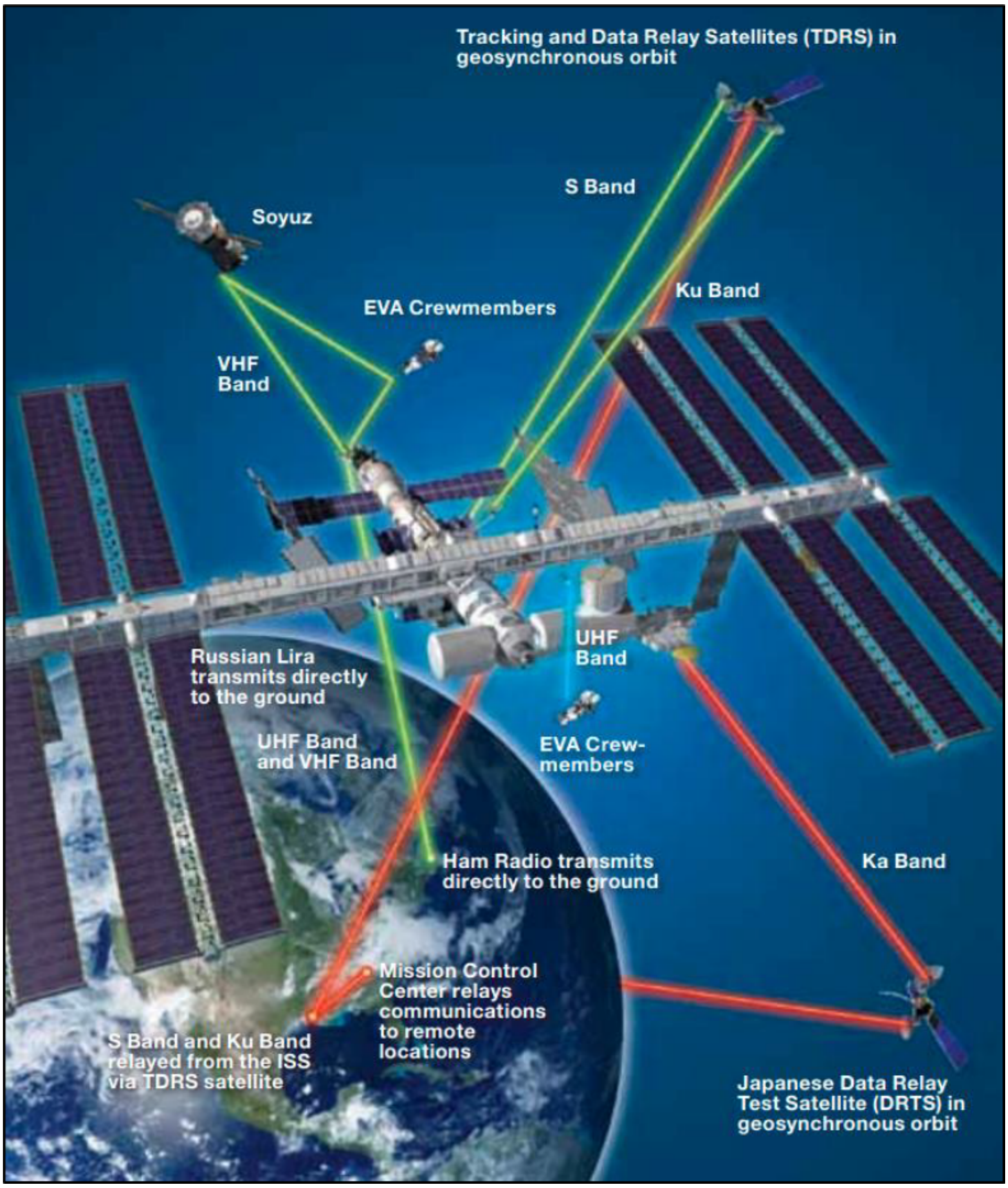

Figure 2.5. ISS Communications architecture 2. Credits: NASA.

has not always been the case. Until 1998, the presence of only two nodes provided a maximum coverage of 85% of the orbit of the ISS. The shadow zone was eliminated with the inclusion of a terminal in Guam, which would allow communication with the station even in the passages above the Indian Ocean. Their use guarantees real-time communication with the Earth by transmitting voice, video, scientific and telemetry data to the mission control center (MCC – H, Christopher C. Kraft Jr. Mission Control Center, Houston). The orbiting station collects the data, converts it into a radio frequency signal and transmits it via antennas from the ISS to the TDRS in line of sight which turn forwards it to the ground – based antennas, located at the White Sands Complex in Las Cruces, New Mexico and at the Guam Remote Ground Terminal. Communication in the reverse direction follows the same logic. In addition to the connection with Earth, the possibility of communicating on board must also be guaranteed, with spacecraft arriving at the station and with crew members during extravehicular activity. The transmission of data also allows the control of all the subsystems that make up the station by the flight operators, the dissemination of videos inside and outside the station and the sharing of data between personal computers of astronauts and controllers.

The Z1 segment of the Integrated Truss Structure, the ISS chassis in which the non-pressurized components are mounted, contains the communication devices used by the USOS. They allow the use of two separate radio links for communications with Earth:

1. S band (2 – 4 GHz) for low data rate audio and video.
2. Ku band (12 – 18 GHz) for audio, video, and high data rate data.

The communication systems used by the US module are five:

1. Audio subsystem for the distribution of voice signals, Warning&Caution (W&C) on board the ISS.
2. S-band subsystem, for the transmission of audio, data, commands, and telemetry through TRDSS.
3. Ku-band subsystem.
4. UHF band subsystem, for audio and data communication between ISS and orbiter or EVA suited crew members.
5. Video distribution system (VDS) for the distribution of video on board the station, on analog or fiber optic channels and interfaces with the Ku system for the transmission of video to earth.

IAS-Internal Audio Subsystem

The Internal Audio Subsystem distributes voice, alarms, and warnings on board the entire station, including the Russian segment. In case of warning the signal is also transmitted outside the ISS, orbiter, or EVA, and to the ground. For this purpose, it interacts directly with UHF band and S-band communication systems. The subsystem consists of three Internal Audio Controllers (IAC, two of them for redundancy) necessary for the control of data communication through the audio system; the Audio Bus Coupler (ABC) to connect all the replacement units in orbit to the fiber optic audio data buses (two redundant buses, one for each ABC to connect it to each IAC); and the Audio Terminal Units (ATU). These devices are essentially phones that allow crew members to listen to alert messages or make calls to other members, public or private up to a maximum of eleven receivers.

The interface units connect the IAS with the S-band and UHF-band communication systems and the orbiter docked at the station. The Assembly-Contingency system /UHF Audio Interface (AUAI) is used to convert the signal transmitted via optical fiber into a digital signal for transmission in S and UHF band. The Docked Audio Interface Unit (DAIU) provides four two-way analog lines for contacts with orbiters during docking and undocking operations.

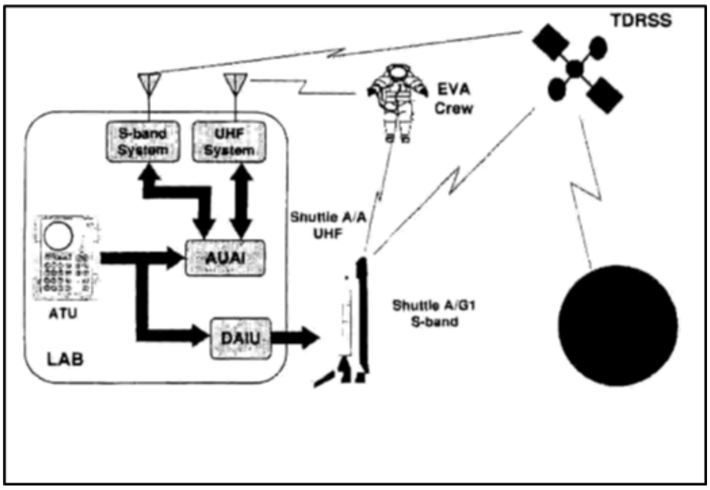

Figure 2.6. Audio Terminal units to Docked Audio Interface Unit and Assembly Contingency/UHF Audio Interface data flow. Credits: [12].

S-Band Subsystem

The S-band system provides two-way communication with ground mission control centers via TDRSS. It receives commands, voice, and files in forward link (uplink) and transmits telemetry, voice, and files on the return link (downlink). It can operate in high and low data rate mode and consists of three elements: the Baseband Signal Processor (BSP), the TDRSS transponder and the Radio Frequency Group with a gimballed antenna and a fixed omni-directional ones.

The Baseband Signal processor has the task of processing, formatting, and deforming, multiplexing and demultiplexing the data. The TDRSS transponder consists of a receiver and a transmitter, creates, and modulates the carrier signal for the return link and receives and demodulates the uplink radio signal. Typical transmission frequency is 2265 MHz. The Radio Frequency Group (RFG) includes an Assembly/Contingency Transmitter Receiver Assembly (ACTRA), a high-gain antenna (HGA) and a low-gain antenna (LGA).

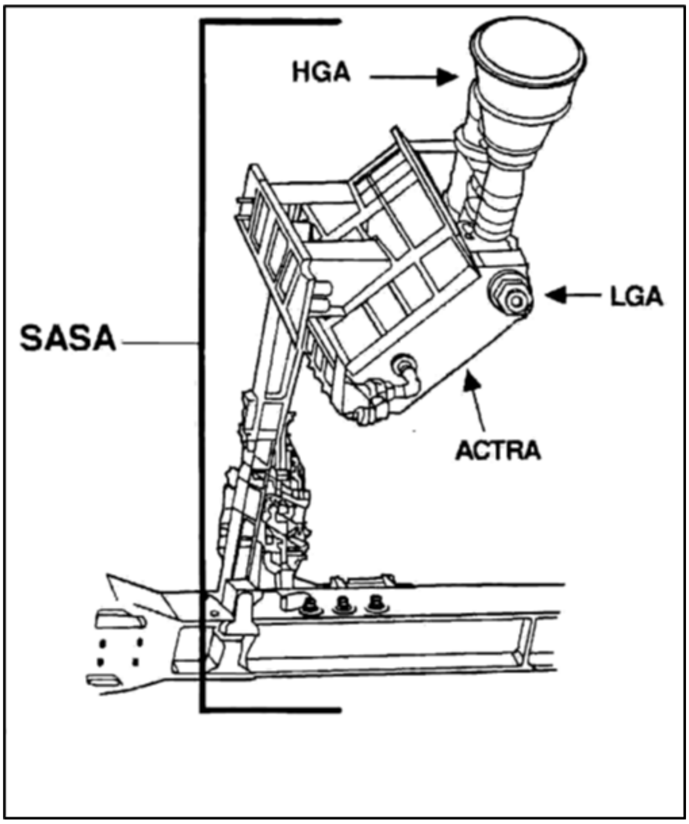

Figure 2.7. S-Band Radio Frequency Group. Credits: [12].

The high-gain antenna is conical and its movement along the sky allows it to be pointed at the TDRS satellites, but it is not possible to communicate directly with the Earth stations. The low-gain antenna is omni-directional, transmits and receives at the same frequencies as the HGA but the signal is diffused within a wider beam.

UHF Subsystem

The UHF communication subsystem of the ISS is one of the subsystems of the space-to-space communication system (SSCS) used for operations in proximity together with the orbiter and the Extravehicular Mobile Unit (EMU). This system allows radio communication between ISS, orbiters, and crew members during an EVA. Its interface with the IAS and consequently with the S-band link allows an audio link between the member in EVA and the ground segment.

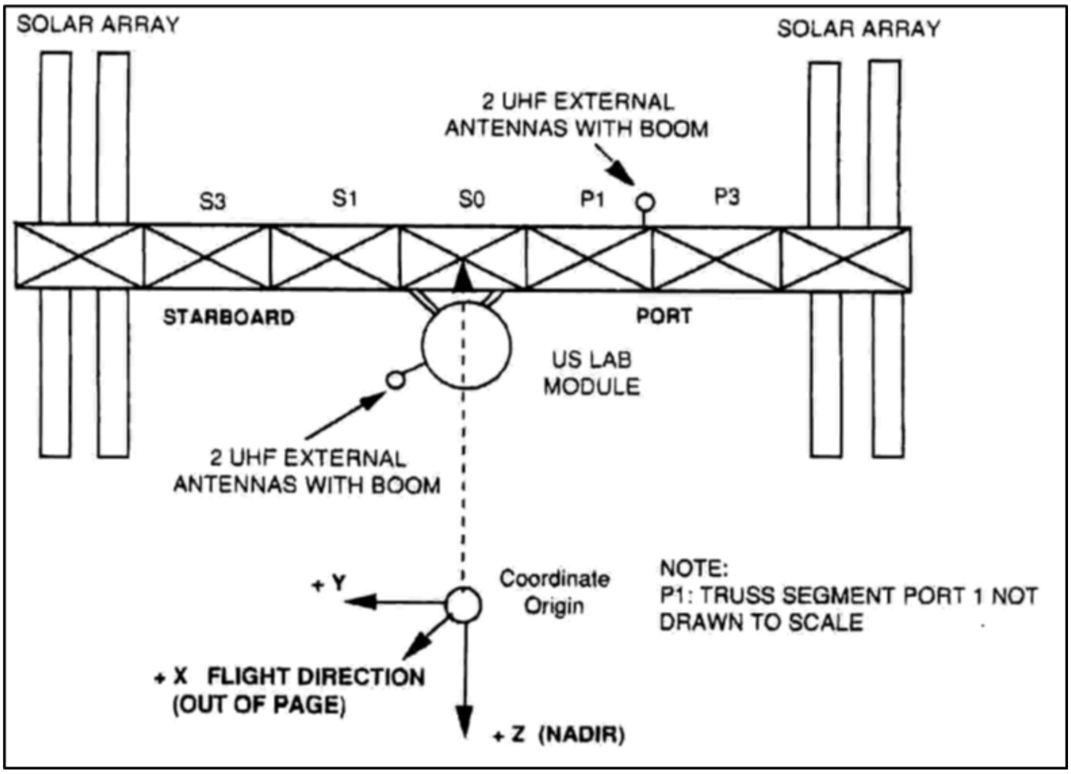

Figure 2.8. External antenna Positions in the UHF subsystem, Credits: [12].

The system supports up to five users connected at the same time and uses a base frequency of 414.2 MHz and a backup frequency of 417.1 MHz. As for the previous subsystems we find the use of a signal processor that plays the role of interface between the transceiver and the IAS, a modem and a radio frequency module for the modulation and demodulation of the signal. Two pairs of antennas for space-to-space communications with external vehicles (Orbiter or EMU suits) are mounted outside the station, but only one pair is in operation during communication as a single transponder can be activated. Inside the airlock there is an antenna for

EVA preparation.

VDS-Video Distribution System

The VDS transmits exclusively video signal to the US, Japanese and European modules, the Russian modules are excluded from this system. The transfer takes place through analog or fiber optic lines, using a PFM (Pulse Frequency Modulation). Among the possible video sources, you can find external cameras, internal recorders, optical payloads; among the destinations, in addition to the various modules, there is the possibility of sending videos to the ground using the Ku-band communication system.

Ku-Band Subsystem

The Ku-band subsystem transmits scientific research data from the ISS to ground stations for all international partners, sends and receives video files and allows participation in teleconferences. In case of unavailability of the S-band communication network, the Ku-band does not guarantee the sending of all telemetry data, but still provides the possibility of monitoring the operation of the systems. Ku-band radiations flight software control protects the health of the crew by preventing them from being in direct line with the Ku-band transmitting antenna, protects the orbiter components and the equipment of the Ku-band communication system from its own radiation reflected from the surfaces of the station. The frequencies used are 15 GHz in downlink and 13.8 GHz in uplink.

Originally, in the early 2000s, data communication between the ISS and Earth was via the Ku-band with a speed of 10 Mbit/s in download and 3 Mbit/s in upload. NASA has continuously improved the service provided by the TDRS. In 2016 it doubled the data rate to 300 Mbit/s in download and 25 Mbit/s in upload. In August 2019 it increased the amount of data transmissible per second up to 600 Mbit/s in downlink.

In case of emergency there is also a backup communication system made by a series of VHF antennas installed in different areas on Earth that allow audio-only communication (voice).

2.1.3 Internet on the ISS

The crew of the ISS first gained access to the internet in 2010. NASA allows astronauts to use a satellite link to remotely connect to a computer located in Houston. This type of architecture allows an advantage in terms of computer security, as if a malicious link is opened by one of the members on board the ISS only the terminal on Earth would be compromised.

Of course, the Internet network supplied on the station is not comparable to the terrestrial one, satellite communication has advantages in terms of availability in places where it is not possible to arrive by cable, but it involves several challenges. The signal during its journey must travel over 70,000 km before reaching its destination and about 150,000 km to respond to a data request from the station. This distance causes a transmission latency of about 0.5 seconds, about 20 times higher than that of a cable connection. In addition to this, the network of TDRS satellites must be kept in the correct orbit by performing station keeping maneuvers that require the use of propellant or energy.

Chapter 3

Communication on the Earth: state of the art

In the third chapter will be presented an in-depth analysis of the state of the art of terrestrial communications. This information will be necessary to better understand the technology you want to use in space.

3.1 Evolution of the cellular mobile network: from the first to the fourth generation

Figure 3.1. Evolution of mobile networks. Credits: Qualcomm presentation @ 5G Tokyo Bay Summit (July 2015).

Mobile communication systems have completely revolutionized communication between people. Over the years, numerous generations of networks and devices have followed one another, each time a substantial change has been presented in the nature of the service (speed, technology, frequencies, latency, applications, etc.) we have moved on to the next generation improving performance and proposing services capable of satisfying emerging needs.

To begin with, it is necessary to rewind the tape and present the history and evolutionary path followed by cellular mobile networks, from their birth to the present day [25] [27].

3.1.1 1G-First generation of mobile network

Over forty years ago, in 1979, the Japanese telecommunications company Nippon Telegraph and Telephone (NTT) developed and created the first generation of commercial cellular mobile network, the 1G network. The first mobile network exploited the use of frequencies usually above 150 MHz and the standard followed was still largely analog. After the Japanese one, during the 80s, many mobile networks were created all over the world: the Nordic Mobile Telephone (NMT) developed in the Scandinavian countries, the Advanced Mobile Phone System (AMPS) born of the American laboratories of Bell and its evolution, the Total Access Communications System (TACS) spread in Europe.

Despite the revolutionary idea put in place, the limitations presented by this technology were still significant. The communications allowed only the exchange of audio signal and not of data packets. A more disabling point was the use of Frequency Division Multiple Access (FDMA) technology, i.e., the possibility of using a frequency band by only one user at a time. In addition, roaming between operators following different standards was not supported, terminals were not enabled to take advantage of different frequencies and communications were not yet encrypted. Anyone with a radio instrument could listen to conversations if tuned to the right frequency. What hindered its spread leading to the need for an improvement in technology was the very high cost to be incurred both for the purchase of a terminal, and for the calls themselves, which in fact made this opportunity a luxury good.

3.1.2 2G-Second generation of mobile network

Its commercialization began in 1991 in Finland along with a new standard the Global System for Mobile communications (GSM).

The second generation of cellular networks has marked a profound change from a technological point of view, being the first digital and commercial network, passing from a few wealthy corporate customers to a mass market. One of the advantages brought with it by digitization is represented by the possibility of encrypting transmissions, making them finally private. To overcome the problem generated using an FDMA technique for access management, it was decided to switch to a Code Division Multiple Access (CDMA) that allows to connect multiple users to the same frequency band simultaneously encoding and decoding the output and input signal. The transition to this new network has allowed the birth of SMS (Short Message Service) and MMS (Multimedia Messaging Service).

After about ten years of life, the spread of the new Standard General Packet Radio Service (GPRS) has allowed the sending and receiving of data packets. Taking advantage of the radio waves of cellular devices, the Internet connection begins to become mobile, creating a 2.5G network.

Despite the great step forward of mobile telecommunications, the data rate was still very low (57.6 kbit/s in download and 14.4 kbit/s in upload) and the costs were quite high: at the beginning of the 2000s in Italy you could pay up to € 0.03 for each kilobit received or sent.

3.1.3 3G-Third generation of mobile network

In 2001, thanks again to the Japanese telephone operator NTT, the third generation of mobile networks was diffused on a commercial scale. This time the standard used in Europe, Universal Mobile Telecommunication System (UMTS), is accepted on a global scale and placed within a family of standards representing the 3G network that working together to allow access to the telecommunications network from all over the world. It represented an evolution of the previous CDMA technique, used starting from the 2G network, which makes it possible to achieve much higher transmission speeds: up to 21 Mbit/s theoretical in download. The frequencies used increase, settling in the bands of 850, 900, 1800 and 2100 MHz.

In the following years, starting from 2008, the communication standard has undergone an evolution that has improved its performance, the 3G LTE (Long Term Evolution) network was born. The introduction of Multiple Input Multiple Output (MIMO) technology was the factor responsible for this change. By allowing the use of multiple antennas at the same time, a terminal was able to exchange a greater amount of data, bringing the download transmission rate up to the theoretical 326.4 Mbit/s.

3.1.4 4G-Fourth generation of mobile network

The first fourth-generation mobile networks began to spread in Europe in 2009, in Sweden and Norway. The first years of life were marked by the coexistence with 3G technology, a factor that generated a lot of confusion in the market of telephone operators. While in the transition from 2G to 3G it was enough to change your SIM, in the transition from 3G to 4G it was necessary to use a new dedicated terminal. With the passing of the years and the increase in coverage areas, 4G has taken over, bringing the data transmission speed up to values between 15 and 25 Mbit/s, this time true and not theoretical. One of the factors that allowed to improve this aspect was the variation of the frequencies used by switching to bands around the 2.3, 2.5 and 3.5 GHz. At this point the limit of the 4G network was no longer represented by speed, but by latency. The spread of online streaming and gaming services has underlined the importance of this aspect, requiring a waiting time, between the request and the actual receipt of a data, less and less.

By re-proposing the development path followed by the 3G network, the 4G network has also evolved. The 4G LTE Advanced and 4G LTE Advanced PRO network were born, bringing data download speeds up to a maximum of 500 Mbit/s. Achieved performances have exploited some key technologies of the next and current 5G network, such as the use of MIMO antennas and the use of different frequency bands for faster data transfer.

Technology	**1G**	**2G**	**3G**	**4G**
Deployment	1970-1980	1990-2004	2004-2010	2010-2020
Data Bandwidth	2 kbps	64 kbps	2 Mbps	1 Gbps
Technology	Analog	Digital	CDMA 2000, UMTS, EDGE	Wi-Max, Wi-Fi, LTE
Multiplexing	FDMA	TDMA/CDMA	CDMA	CDMA
Primary Service	Analog Phone Calls	Digital Phone Calls and Messaging	Phone calls, Messaging, Data	All-IP Service (including Voice Messages)
Key differences	Mobility	Security, Mass adoption	Better Internet experience	Faster Broadband, Internet Lower Latency

Table 3.1. Comparison of all generations of mobile technologies. Credits:[28].

3.2 5G-Fifth generation of mobile networks

The fifth-generation mobile network is the most complex to have ever been developed as it must cope with a new need, it must be enabling for other types of technologies. It was born as an expression of the maturation and convergence of a series of technical-economic trends: the spread of mobile access, the exponential increase in the performance of hardware systems combined with the reduction of costs, the progress in the development of Artificial Intelligence and smart things, increasingly performers from the point of view of communication, processing, and storage of data. For this reason, the 5G network will represent much more than a natural evolution of the 4G LTE network with new access systems, greater bandwidth, higher performance, and low consumption. It heralds the birth of a new era; an innovative network platform and end-to-end services able to meet the demands of consumer markets and the businesses of digital companies. 5G will bring with it a real systemic revolution, in addition to the improvement of already traditionally mobile market segments, it will perform the function of technological enabler to make new branches of the market "wireless"[5] [18].

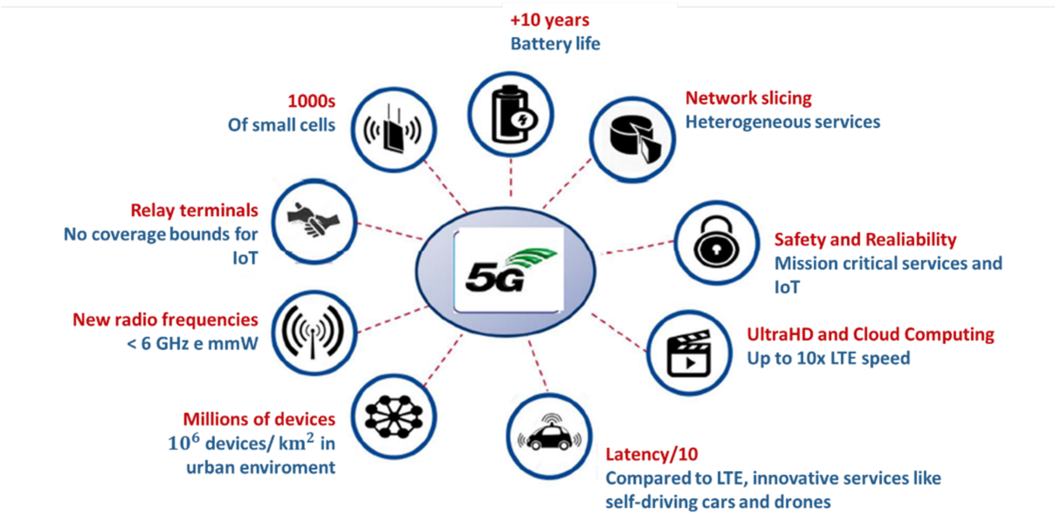

Figure 3.2. 5G strenghts. Credits: TIM S.p.A., internal presentation.

3.2.1 User and application trends

In everyday life, mobile devices play various and constantly evolving roles, so new communication technologies will have to be able to support the new emerging use cases. They will be increasingly demanding in terms of data rate, number of connected devices and reliability offered by the service. In this regard, a network will be needed in which mobile broadband is still an important driver, but it is no longer the only one, as was the case in 4G technology. The focus will no longer be on the service offered but will be centered on the needs of the user. The new network will support very low latency and very high reliability connections, whether they are Human – Centric, or Machine – Centric. People expect to live an instant and always available connectivity experience, fundamental factors for the development of cloud, virtual reality, and augmented services. Obviously, the service will have to maintain a high-quality level in terms of the volume of data exchanged, even with the device in motion. Another aspect that should not be underestimated is the continuous growth in the number of connected devices, their complexity, and their potential. One of the objectives will be to be able to take full advantage of them, so access must be guaranteed even in the presence of many connected users, such as a crowded square or urban transport. This trend will continue in the short future following the concept of the Internet of Things, many objects of common use will have the possibility to connect by cable or wireless to exchange information and improve the services offered, going to exponentially increase the number of devices simultaneously online. Along with the number of terminals, the number of services and new applications that require a connection to the network is also increasing. Cloud, public safety, or health communication services are just a few examples of new emerging businesses.

3.2.2 Usage Scenarios

The areas in which the new 5G network will be applied are, therefore, very heterogeneous, with different requirements and technical characteristics. In this respect, the network will must make flexibility its strong point, which explains why it uses a series of frequency bands with very different properties. From lower frequencies (694 – 790 MHz) to have a greater range at lower transfer rates, to higher frequencies (26.5 – 27. 5 GHz) that guarantee the very fast transfer of little data, passing through intermediate solutions (3.5 – 3.8 GHz). In addition to this aspect, it will be able to provide reduced latency, high reliability, and the ability to support a massive number of devices connected simultaneously to potentially allow each everyday object to be interconnected and exchange information (IoT – Internet of Things). In fact, we will move from a 4G network focused on data transfer speed, to a 5G network with multiple dimensions, customizable according to customer needs. The figure below was released by the International Telecommunication Union (ITU) within the ITU-R Recommendation M-2083-0. It graphically represents the three operational dimensions within which you can configure the network and its application scenarios:

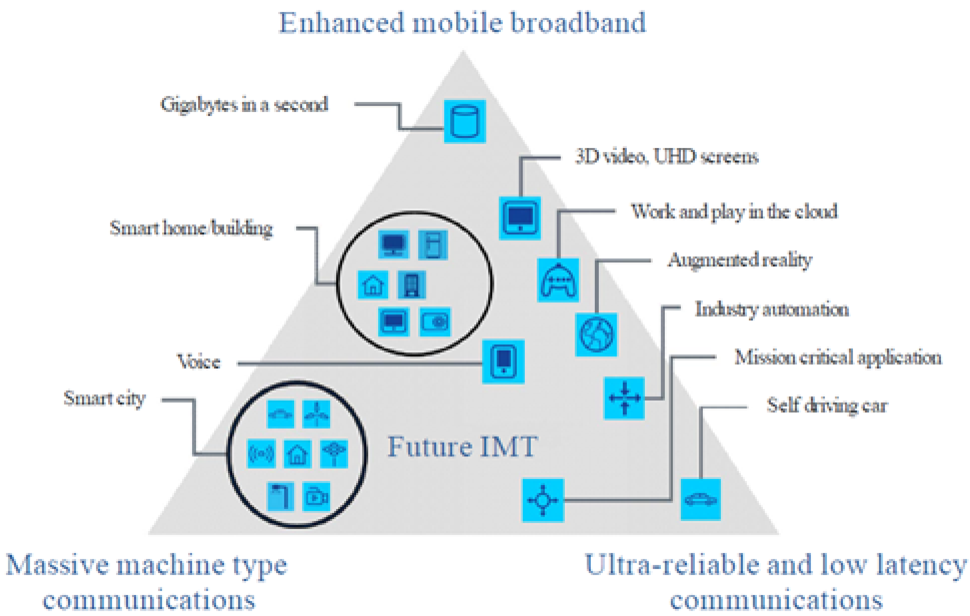

Figure 3.3. Usage Scenarios of IMT for 2020 and beyond. Credits: [26].

1. *Enhanced Mobile BroadBand (eMBB)*: this is the development dimension already present in previous generations of mobile networks, but it brings with it upgrades compared to them and allows access to ultra-broadband Internet. Innovation and improvement will be based on three main areas: increased capacity with broadband access, management of more devices using large volumes of data, and increased user mobility.The increased broadband access capacity will allow an extension of cellular coverage to include offices, parks, shopping malls and large crowded spaces. It is precisely in these places that the need to provide access to the network to many terminals at the same time will come into play, ensuring fast, efficient, and low-cost data transmission, a fundamental driver for the dissemination of the service and associated applications. Finally, it must also be possible to use access to the broadband network on board moving vehicles (cars, buses, trains, planes, ships and means of transport of various kinds).The development of this capability will allow to reach applications that require high data rate, such as Virtual and Augmented Reality, diffusion of streaming media and UltraHD video, online gaming, and cloud use.

2. *massive Machine Type Communication (mMTC)*: represents the most futuristic development dimension of the three. Forecasts state that in the coming years the number of objects connected to the network will exceed the number

of humans even by orders of magnitude. The massive IoT that is expected will come to life starting from Smart Homes, passing through Smart Buildings, up to creating real Smart Cities, in which every service and object will be able to exchange information with what surrounds it. For this purpose, it is necessary to work to increase even more the number of devices that can be connected simultaneously, decrease the cost of terminals, and increase the life of batteries.

3. *Ultra Reliable – Low Latency Communication (URLLC)*: this area of development will serve to support all those applications that require high reliability, almost instant connectivity (with very low latency) and guaranteed security. The result will be a connection almost comparable to a wired fixed network and will support activities such as self-driving vehicles for moving people and for agriculture, complex automation machinery, remote medical surgery, and Mission Critical Services (MCS), services whose failure is not a possible option.

New and different usage scenarios will emerge over time. Flexibility in managing network features will come in handy to meet all network requirements.

3.2.3 Characteristic and capabilities

The IMT for 2020 and beyond expects to be able to provide a network with far better capacities than previously used networks. The variety of possible usage scenarios and related requirements is tightly coupled with the characteristics of the 5G network. As mentioned above, the key design principles are the flexibility and diversity of services that can be proposed to meet the demands, varying the main parameters that define the network properties.

The eight key parameters considered and defined by the IMT – 2020 [26] will be presented below:

1. *Peak data rate: Maximum achievable data rate under ideal conditions per user/device (in Gbit/s).*

2. *User experienced data rate: Achievable data rate that is available ubiquitously across the coverage area to a mobile user/device (in Mbit/s or Gbit/s).*

3. *Latency: The contribution by the radio network to the time from when the source sends a packet to when the destination receives it (in ms).*

4. *Mobility: Maximum speed at which a defined QoS and seamless transfer between radio nodes which may belong to different layers and/or radio access technologies (multi-layer/-RAT) can be achieved (in km/h).*

5. *Connection density: Total number of connected and/or accessible devices per unit area (per km^2).*

6. *Energy efficiency: Energy efficiency has two aspects:*

   (a) *on the network side, energy efficiency refers to the quantity of information bits transmitted to/ received from users, per unit of energy consumption of the radio access network (RAN) (in bit/Joule).*

   (b) *on the device side, energy efficiency refers to quantity of information bits per unit of energy consumption of the communication module (in bit/Joule).*

7. *Spectrum efficiency: Average data throughput per unit of spectrum resource and per cell (bit/s/Hz).*

8. *Area traffic capacity: Total traffic throughput served per geographic area (in Mbit/s/m^2).*

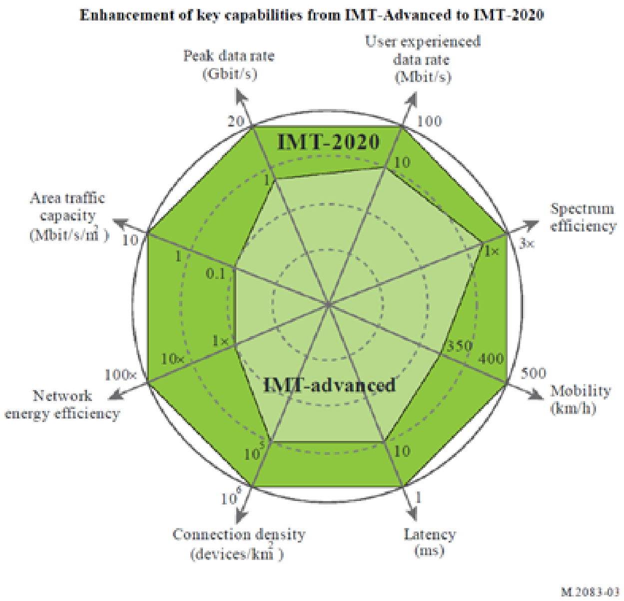

Figure 3.4. Enhancement of key capabilities from IMT - Advanced IMT – 2020. Credits: [26].

The diagram represented in figure 3.4 compares the values achieved by these parameters for the IMT – Advanced standard and the research and development targets for the new IMT – 2020.

The maximum achievable data rate for enhanced mobile broadband is expected to be around 10 Gbit/s and up to 20 Gbit/s under conditions and scenarios. The strong point is, however, the possibility for users to take advantage of a varied data rate depending on the environment that surrounds them. For example, in urban and sub-urban areas the 100 Mbit/s can be reached, in case of hotspots you will also have higher data rates available, up to 1 Gbit/s. Remaining in an urban scenario, the maximum supported connection density will be equal to one million devices per square kilometer. The IMT – 2020 will support a traffic capacity of up to 10 Mbit/s/m^2 with a spectrum efficiency up to three times higher than the previous standard, obviously the usage scenario will affect the actual value achieved. Through the air, the new technology will be able to provide a service with a latency in the order of milliseconds and with an acceptable quality even in the case of mobility up to 500 km/h. Finally, the energy consumption for radio access to the network will also be contained by respecting the parameters to be achieved. To this end, the energy efficiency of the network will be improved by at least the same factor as the increase in performance compared to the IMT – Advanced standard.

As highlighted earlier, the ability to adapt network characteristics to the usage scenario is critical. The following figure represents the network configuration for a scenario that focuses on enhanced mobile broadband, one on ultra-reliable and low latency communications and the last one configured for a massive machine-type communication.

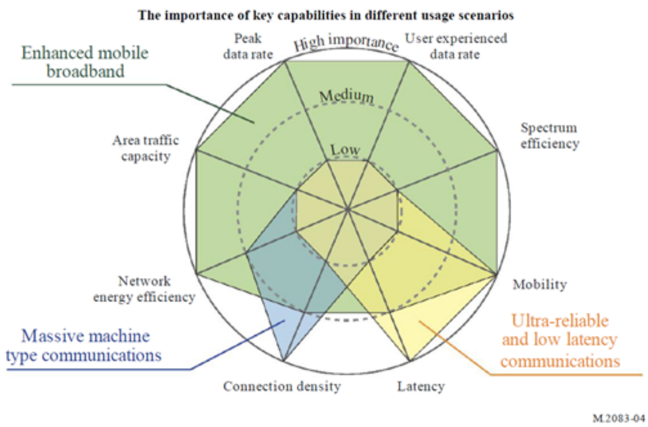

Figure 3.5. The importance of key capabilities in different usage scenarios. Credits: [26].

As can be observed, the parameters were scaled according to three levels: high, medium, and low.

1. In the Massive Machine – Type Communication scenario it is essential to guarantee a high connection density given the incredible number of devices to be supported, which will probably transmit occasionally and in a scenario with almost zero mobility. A high battery life and a low cost are required for this type of scenario.

2. In a scenario of ultra-reliable communications and low latency, of course minimal latency is required for all critical applications. This is accompanied by the need to support high mobility in the event, for example, of emergency transport.

3. In the Enhanced Mobile Broadband scenario, almost all parameters have a high importance: user experienced data rate, peak data rate, area traffic capacity, spectrum efficiency, mobility, and energy efficiency. In this type of scenario, you can accept higher latency and simultaneous connection of fewer devices to improve network performance.

3.2.4 Technologies to support the 5G network

The 5G network will not be able to achieve the promised performance like a fiber optic wired network just by using a new and better radio interface. The entire infrastructure will have to present unprecedented flexibility, support a greater flow of communication using multi-radio access technologies and design new proposals necessary to meet emerging requirements.

This document will present techniques and technologies such as Network Slicing, Network Function Virtualization (NFV) and Software Defined Networking (SDN), the massive use of Multi-Input-Multi-Output (MIMO) devices that take advantage of Beamforming and Multi-access Edge Computing (MEC)[3].

Network Slicing

In the coming years, the 5G network will support several heterogeneous services, each with its own characteristics in terms of performance, availability, and scalability. To enable these services to be as well as possible, they should be designed and operated by those who have an interest in marketing, a kind of rental of a slice of the entire mobile network to offer their service. In this case, the flexibility of the service offered by 5G networks comes back into play, as the entire network would be divided into independent network sections, each configured according to the needs of the service provider. An important note is to be made with respect to the roles played in the network division, the mobile operator will be responsible for the provision of the connectivity service, while the role of service provider could also be played by a different entity. Working in this perspective it becomes possible to offer very heterogeneous characteristics while taking advantage of the same infrastructure, since each section of the network will be managed and configured according to the specific requirements of the service provided.

Figure 3.6. 5G Network Slicing. Credits: NOKIA.

Network Function Virtualization (NFV) and Software Defined Networking (SDN)

Network Function Virtualization (NFV) and Software Defined Networking (SDN) will be two of the main technologies of 5G, which will allow to achieve high levels of flexibility and programmability. SDN will decouple software from hardware systems, NFV is the set of technologies needed to support virtualization of most network functionality. With the definition of software and hardware on two different levels it will be, therefore, easy for the network infrastructure to adapt quickly and effectively to the new demands of the market: the software will become increasingly open source, while the hardware will be standardized also reducing production costs. In the future, the network operator will only have to manage a growing multitude of software features and processes, which can be allocated to predefined hardware. Functions traditionally dependent on hardware will be located within a cloud infrastructure, managed, and controlled remotely through an autonomous service. Through the continuous use of updates, operators will be able to keep applications in "executable" status without having to necessarily interrupt the service for their customers.

In the last period the concepts of "software-defined network" and "virtualization of network functions" have become increasingly important in the world of telecommunications. They are independent concepts, but which together can guarantee even greater advantages and revolutionize the construction and management process of telecommunications networks.

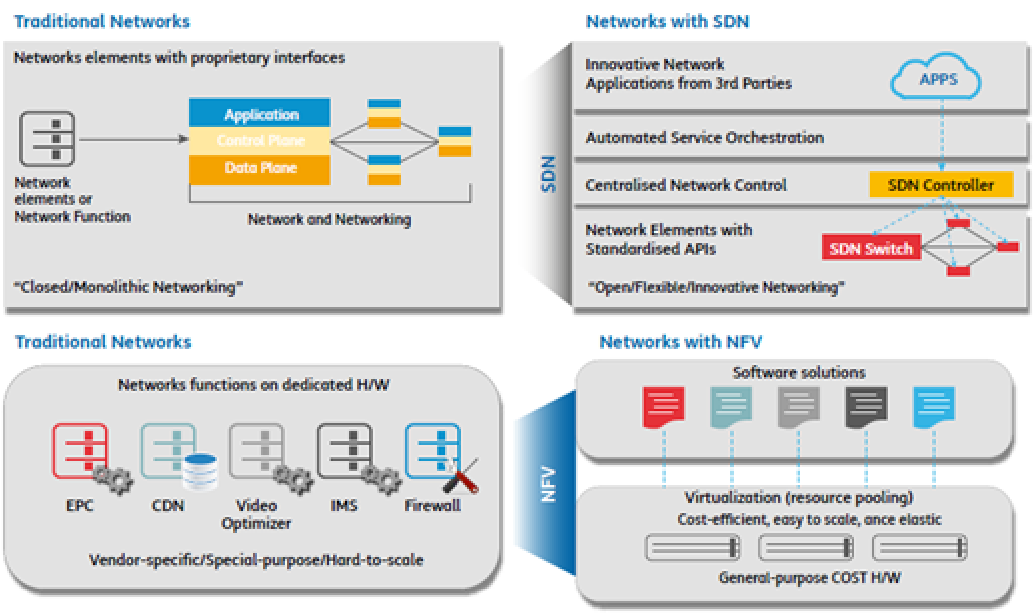

Figure 3.7. SDN and NFV. Credits: Tim S.p.A. Internal Presentation.

Massive MIMO and Beamforming

Multiple Input Multiple Output (MIMO) technology exploits multipath, a natural phenomenon of radio waves. Without it being necessary to increase the transmission bandwidth it is possible to increase the data rate: the output signal from different sources will reach the receiver following more than one path and with slightly different arrival times as during its journey it will meet bodies that will generate reflection phenomena. In fact, it will transport several streams of data at once, increasing their volume. Although this technology is already being applied in the telecommunications sector by LTE and Wi-Fi networks, the goal is to increase the number of antennas to further improve performance. With the massive application of this technique an access network will be created in small macro assisted cells, in which the macro cell will take advantage of lower bands to provide traffic in an omnidirectional way while the small cells will use the millimeter wave band to provide traffic through highly directive beams. They will present high emission power levels small size to mitigate signal losses on the path. Thanks to the possibility of directing the signal beam, its modeling(beamforming) can be horizontal and vertical, allowing to reach any direction in which the end user is located. In this way the signal will be sent only when necessary, decreasing possible interference and reducing energy consumption.

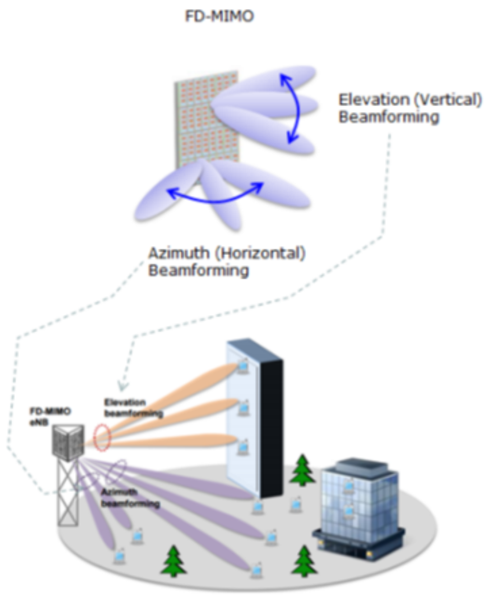

Figure 3.8. MIMO and Beamforming. Credits: Tim S.p.A. Internal Presentation.

Edge and Fog Computing

One of the evolutionary elements proposed by the new 5G network is the possibility of supporting low-latency services even in mobility conditions. To succeed in this aim, the processing of the data requested by the user or by the terminals must take place at the edge of the network, according to the concept of Multi-access Edge Computing. It provides for the transfer of sites even to the peripheral places of the network as well as near the source of the data. This will reduce the distance between user and source allowing faster data processing, reducing service latency times. In addition to this, this solution will also allow a decongestion of the traffic sources in upload to the Cloud, managing in a simpler way than local sources. The latter aspect will add an extra layer of security for the user's sensitive data, as his data will remain private, without the need to transfer to a public cloud for processing.

Often Edge and Fog Computing are associated and almost confused. Although both allow data to be processed closer to the end user to reduce latency times and filter data, the two techniques differ in the actual location of the terminals. Fog computing allows the validation and processing of data in the local network, processing them in a”fog” node. In fact, it represents the missing link between the data that must be transferred to the cloud and those to be analyzed locally, at the edge of the network. Edge computing transports them directly to devices at the edge of the network, such as routers or wireless networks where they are processed locally.

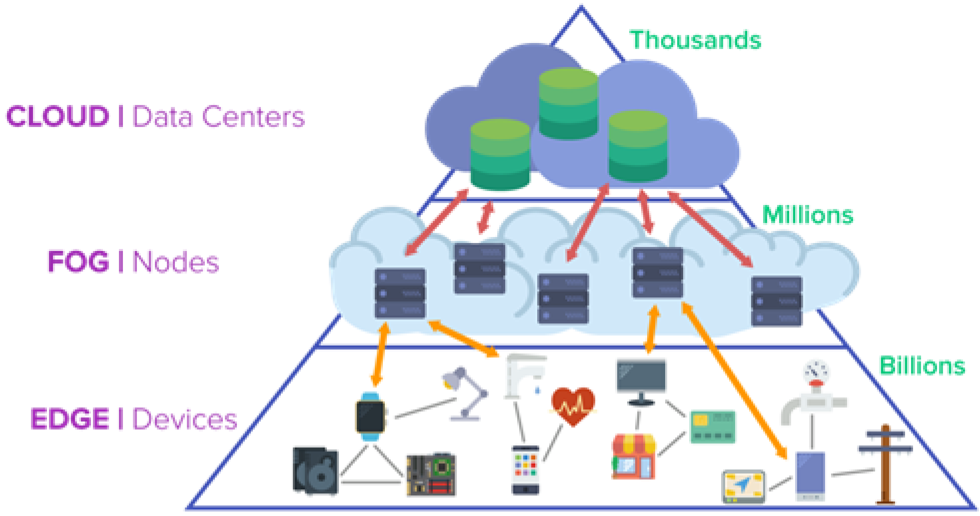

Figure 3.9. Edge and Fog Computing.Credits: [20].

Chapter 4

Space applications for mobile networks

Figure 4.1. Moon base artist concept. Credits: [10].

Over the last decade, the world's major space agencies, such as the US-based NASA and the European ESA, have begun to lay the foundations for establishing a continuous and sustainable future space exploration. Of course, the first objective is represented by the return of the human being on the lunar surface, this time not for a touch and go, but to give life to a real extraterrestrial colony. Subsequently, the same type of approach can be used for the creation of establishments on other celestial bodies. The focus should be on the adjectives "continuous" and "sustainable". Once we reach the surface, we will proceed with the construction of a habitat that allows human life, to maintain a lunar base always inhabited by astronauts, a bit like what currently happens with the International Space Station. The structure must also comply with sustainability requirements; it will have to be self-sufficient in terms of the resources necessary to support human and constructive life, in this way the colony can expand itself to create a small lunar village.

The Moon Village will be a very complex system that will have to be subject to very strict operational and related to human safety requirements. In addition, it will necessarily have to be an open and expandable system, able to relate, interconnect and integrate with the other elements present on the surface, in orbit and even with the mission control centers on Earth.

One of the most important aspects will be interplanetary communication and navigation. Lunar explorers must always be in contact with the staff that manages the mission, so the possibility of transmitting not only audio signals (voice), but also data packets will be essential. This aspect will provide the possibility to stream high-definition video, to supervise the operating status of structures and equipment through the exchange of telemetry data and to maintain control of the biometric parameters of the astronauts. The communication network will not only have to offer a radio bridge for contact with the Earth but will also have to cover all operations directly on site on the lunar surface. A connection between explorers and static and moving devices on the ground will be needed to offer the possibility of remotely monitoring and controlling sensors, instruments, and rovers in motion.

Currently, the research conducted by NASA and ESA for the provision of a navigation and communication service has led to the selection of two possible approaches: a first solution that provides a well-structured and extremely expensive architecture, composed of constellations of satellites and orbiting elements; or a second proposal with an ad-hoc infrastructure created, which is flexible, scalable and uses COTS (Commercial Off the Shelf) technologies and components. Returning to the constraint of sustainability of space exploration, it seems that the second way is the most viable. In addition, the possibility of using COTS components for the realization of a scalable network would also guarantee a simplification of the process of development and design of ad-hoc technological devices for the lunar base [10].

At this point the choice falls on the use of LTE communication technology, currently widespread on Earth, with a direct and already well-defined look and path towards the fifth-generation technology 5G, still in the process of settling. The fact that it is well stable on terrestrial networks, it presents an economy of scale and uses the standards already accepted on a global scale (IEEE 802.16 WiMAX standard), represent other points in favor of the use of 5G technology as they could lead to the participation of many companies and a reduction in costs.

The use cases it will have to face will be many and some probably not yet identified and defined, but they can be traced back to two main categories [17]:

1. Low data rate and reliable connection; for applications that provide for the monitoring and control of the outpost and its devices, essential audio, and video signals. In this case the service must be highly available, it is estimated in at least 99.99% of cases, as well as in cases of emergency and disaster.

2. High data rate: for services that include high-definition audio and video transmission, file and data sharing, http surfing, and cloud access. In this case we are satisfied with a lower availability, but still equal to 98% of cases.

From these requirements 5G technology represents an excellent candidate for use on the lunar surface, given, moreover, its ability to support a wide range of applications that move within its three dimensions: massive IoT, Mission Critical Control and enhanced Mobile Broadband.

From the point of view of performance, it will offer high data rates even in the presence of numerous users in a confined space, very low latency and wide coverage connections, minimization of energy consumption, programmability, and configurability for the multiplicity of services.

Once the technology is chosen, it will then be necessary to work on the definition of the distribution of the cells that will make up the network on the lunar surface. Obviously, this aspect will depend on the requirements imposed and the physical characteristics of the chosen place, as well as on the technical properties of 5G.

As for the navigation service, or better defined as Positioning, Navigation and Timing (PNT), ESA has carried out some feasibility studies that have led to the conclusion that 5G technology, based on the IEEE 802.16 WiMAX standard, is useful to implement this service only at a short distance, up to a maximum range of 8 km. Once these distances are exceeded, it will not be possible to guarantee these functions using only ground infrastructures, elements in orbit will be needed to complete the network.

Just like the 4G LTE standard, the multi-carrier waveform of 5G allows the transfer of a pilot signal useful for positioning services. This signal can be used to measure the distance by evaluating its time and its angle of arrival (Time of Arrival – ToA, Angle of Arrival – AoA). On Earth these applications rely on the signal of the GNSS (Global Navigation Satellite System) and for the lunar base we will try to use the same type of approach. In the future, such a solution for Martian exploration will not be applicable, so miniaturized atomic clocks will need to be used.

4.1 Critical issues and solutions

The space environment and, even more, the lunar surface present a very different environment from the terrestrial one, with extreme conditions. The components chosen to build the communication network will have to survive in this habitat and precautions will have to be taken during the production phase, making some small changes. Nokia, after being chosen as a partner by the Berlin startup Part Time Scientists before, and by the US space agency NASA after, has conducted studies to understand the critical issues to be faced for the construction of an interplanetary network. The research has led to some proposals, including a focus on the possibility of applying these teachings to our advantage also in the terrestrial field [22].

4.1.1 Environmental conditions

The network that will be created on the lunar surface will have to survive extreme environmental conditions. The temperatures reached will be very low in contact with the surface and the temperature range produced by solar lighting is considerable given the lack of atmosphere. This also leads to massive radiation exposure and the need to operate in a vacuum. Another aspect to consider is the presence of lunar dust, highly abrasive, which can superficially damage the components. To cope with these problems, the choice of materials adopted will be a fundamental factor. The components must also have radiative and/or conductive cooling/heating methods to keep within their operating temperature ranges. The mitigation of the effects due to radiation will take place through tests carried out on the components to evaluate the errors generated. Finally, the equipment will be coated with conformal coating to ensure additional protection.

On Earth you will probably never have to experience similar environmental conditions, but this could still prove useful in remote areas with environmental conditions challenging to current technology, such as deserts or Arctic areas.

4.1.2 Mechanical conditions

Before being usable on the lunar surface, the network will have to make the space journey to reach our satellite and obviously on its arrival it will not be able to present damage. After transport to the launch site, the components will have to deal with the extreme accelerations, shocks, and vibrations due to the launch and landing phases on the lunar soil. To overcome this challenge the hardware will have to be more resistant and hardened, so we will have to work on the mechanical and thermal design of the components. On Earth in mining environments, onshore/offshore oil and gas drilling sites, or wind farms the components find themselves exposed to similar conditions. They are probably less extreme but being able to withstand a more hazardous operating environment will help in the development of technology for the terrestrial environment.

4.1.3 Physical footprint

For a space mission, the space allocated to the payload within the spacecraft is limited. In this case the devices will be stored inside the lunar module that will land on the surface, so the space available will be even less. It will be necessary to balance aspects such as weight and size of the components, while still managing to guarantee the functionality provided for the network. To submit to this constraint, ultra-light components compacted into a single hardware will be used and by integrating it with software, the number of elements will be reduced. 5G technology is even more useful from this point of view.

The solution of an "all – in – one" network could be useful in remote places on Earth, for rescue operators in areas with possible communication network malfunctions following catastrophic events.

4.1.4 Power consumption

Each function and operation that will be carried out by the rovers and landers, in addition to the devices of the entire telecommunications network will have to be powered using batteries or, mainly, solar panels. The challenge lies, therefore, in being able to minimize the energy consumption of the components. The lunar network software will be integrated into a minimum number of electronic boards that will divide the resources present, consequently saving and energy. Smart mechanisms like LTE Smart Scheduler will also reduce overall power consumption.

Public safety, emergency response or remote areas services may have limitations on the amount of energy available on Earth, perhaps due to the non-continuous production of energy by wind, solar or electric vehicles. Research and innovation in this field could bring benefits in the terrestrial environment.

4.1.5 Distance and access

The distance between the Moon and the Earth amounts to about 384,400 km. Of course, sending dedicated personnel to solve problems on site is not an option. From this point of view, the components must be designed to be autonomous, able to manage their maintenance, configuration, deployment and to cope with any failures. It will take the design of an Operations and Maintenance system and the inclusion of a limited redundancy 1+1 both in terms of hardware and software to mitigate the impact of a problem. A fundamental ability will be a rapid reboot of the system in case of failure. As with previous applications, this innovation could be useful for all land-based areas that are difficult to access, to manage the operation and maintenance of components and structures.

4.1.6 Reliable connectivity

The presence of man on the Moon in the long term will be greatly facilitated thanks to a highly reliable network of connections that will allow to carry out some exploratory and cognitive missions fundamental to NASA programs. The challenge is, therefore, represented by the construction of a wireless network that is stable and entrusted to them. It must be available between landers, rovers, explorers, lunar base, or any other user in motion. In addition, the characteristics of the lunar soil and the exploration areas, rich in craters and reliefs, will make this operation even more complex, also given the non-possibility of carrying out inspections for the planning of the network. The choice of the 4G LTE network, made by NASA, shows how it is considered an already mature technology and able to guarantee stability and reliability in a multitude of different contexts on Earth. This experience will bring to Earth new configurations of the network, new uses that will help to make progress in the process of transforming current environments into homes, buildings, and smart cities.

4.2 First approach: Mission to the Moon

In March 2018, the plan for the construction of the first cellular network node on the Moon was announced. Vodafone as a mobile network operator and Nokia as a technological partner take part in this project. The network chosen for the completion of the test is that of the fourth generation 4G, as 5G is still considered an emerging technology and not ready for a similar scenario. The idea is to mount a base station near the lander that will be left in the Taurus-Littrow valley, scenario of the Apollo 17 mission and of the Mission to the Moon of which the project is part. These instruments will serve for testing the live transmission of high-definition video from the lunar surface to the Earth's [11]. The mission, planned to start in 2019, has never seen life, so what remains are only the tests carried out on Earth and the experience gathered by the companies involved, but let's take a step back.

Figure 4.2. Mission to the Moon logo. Credits: [11].

4.2.1 Part Time Scientists

The organization of the mission was taken care of by PT Scientists (Part Time Scientists), a private Berlin scientific and engineering company with the aim of trying to reduce the costs of space exploration, making access to space within everyone's reach. One of the company's key thoughts is to involve unconventional private

Figure 4.3. PTScientists logo. Credits: pts.space3

partners in space activity to build sustainable space exploration and provide more cost-effective opportunities for space research activities. It was originally founded in 2008 to compete in the Google Lunar XPRIZE competition, which ended in 2018 without a winner.

4.2.2 Mission to the Moon

The main objectives of the Mission to the Moon were to be able to organize the first private mission with landing on the lunar surface, conducting, once on the ground, scientific and technological experiments in the field of telecommunications.

Figure 4.4. Mission to the Moon Key partners. Credits: [11].

In addition to Vodafone and Nokia, key communications partners, AUDI, for the development of rovers that would beat the lunar terrain, and some space agencies such as the European ESA and the German DLR were included.

The project was planning a series of missions that would lead to an increasing number of experiments and knowledge necessary to allow man to move permanently to the Moon. Starting from an exploratory mission at the Apollo 17 landing site and full of technological demonstrations, it would have come to missions lasting several years and the construction of long-term housing infrastructure to support human life and exploration.

Below you can see in more detail the timeline planned for the entire series of missions.

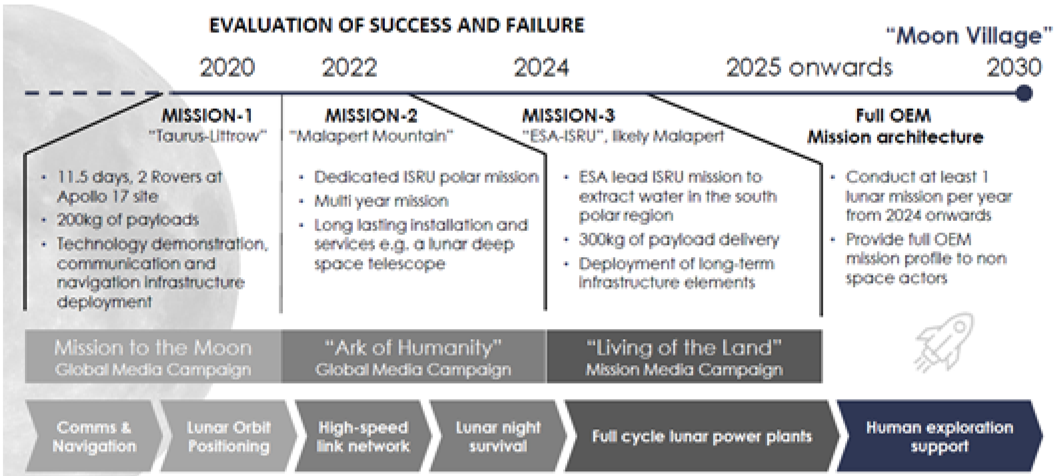

Figure 4.5. Mission to the Moon timeline. Credits: [4].

The first mission, Mission to the Moon, involved touching the lunar soil in the Taurus-Littrow Valley to perform scientific experiments on the wrecks of the Apollo 17 mission [4]. In particular, the Lunar Roving vehicle was abandoned on the surface in 1972 and one of the elements of greatest interest for the mission was the study of the response of its chemical-physical structure to over fifty years of exposure to the space environment. This process and the exploration of the entire surrounding area would be filmed and shared via high-definition videos sent directly to Earth, giving rise to the first extraterrestrial live stream in the history of mankind. The task would have been carried out by two Audi Lunar Quattro rovers (ALQ rovers), capable of deploying a series of technological payloads useful to show new ways of exploring space and remotely controlled from Earth. They would be led to the lunar surface by the ALINA (Autonomous Landing and Navigation Module) spacecraft, capable of carrying up to two tons of payloads and compatible with most current launchers.

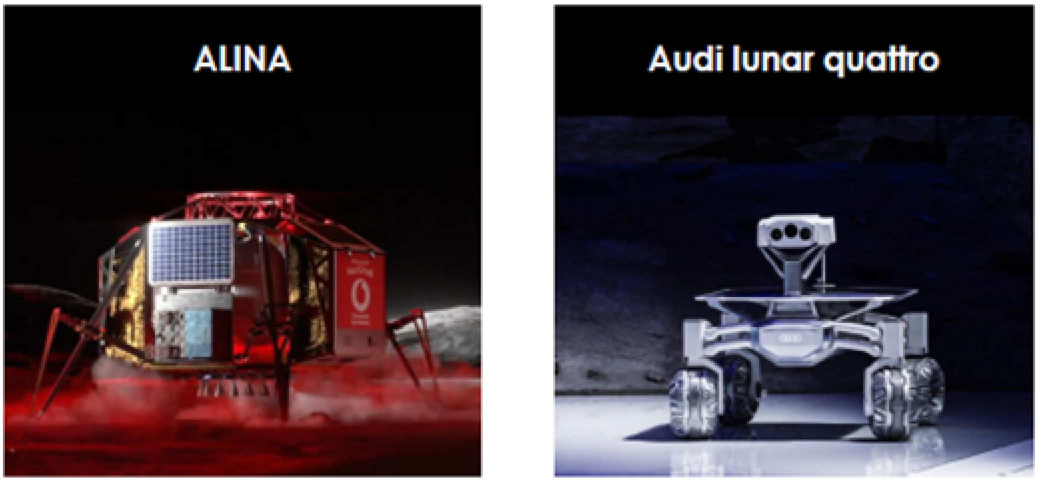

Figure 4.6. ALINA module and Audi Lunar Quattro Rover design. Credits: [11].

The two ALQ rovers and the ALINA lander would create the first 4G – lunar LTE network, in collaboration with Vodafone, Nokia and Nokia Bell Labs [11]. In addition, the great advertising campaign planned, not only by the mobile operator but also through agreements with the Red Bulla Media House, would have tried to capture as many audiences as possible within the whole world to draw new supports for future missions.

4.2.3 Lunar Network Demonstration

The focus from a telecommunications perspective was to achieve the ability to send high-definition video to Earth. To achieve this, some key requirements have been identified for the network to be used:

1. Minimize power consumption by keeping it below 45 Watts.
2. Ensure a wide-ranging connection, over 4 km of distance between the base station mounted on ALINA and the user equipment available to its ALQ rovers.
3. High bandwidth, at least 2* 2Mbit/s.
4. Robust.
5. Economic.
6. Scalable.

7. It can also be used on the move, a fundamental requirement given the task of rovers.

Among the candidate network technologies to carry out this task, the 4G LTE network has emerged. The low consumption, the large number of users in the terrestrial environment and the low costs have dominated it. In addition, the 4G network can manage a multi-cell network architecture allowing roaming between them, has a high spectral efficiency, turns out to be a technology that can be easily integrated and with large development teams behind it all over the Earth.

The mission architecture involved the use of the Vodafone LTE network for connections between the ALINA base station and the user equipment on board the two ALQ rovers using a variable data rate between 2 and 50 Mbit/s. This part of the architecture would have constituted the real technological demonstration. As regards, instead, the direct communication channels between the three vehicles and the Earth, it would have been opted for a radio frequency connection in S-band or X-band (ESA ESTRACK Based Communication) or for the test of a laser communication for the channel between the lander and the ground station. Each solution would be matched by a different data rate and was summarized in the following image.

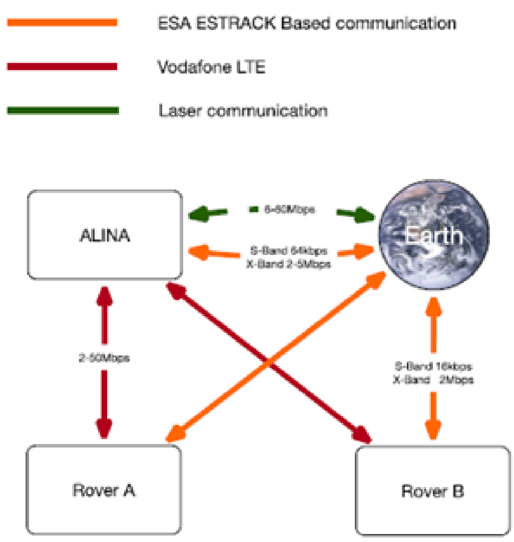

Figure 4.7. Mission to the Moon communication architecture. Credits: [11].

One of the advantages of using the mobile network for communications over a more common communication system lies in the reduction of energy consumption.

The studies carried out for the realization of this mission have shown that the same rover, Audi Lunar Quattro, equipped with a system that exploits the LTE network provided by Vodafone has an energy expenditure for radio communication equal to one third of that of a normal equipment. The total required power values decrease from 100 W to 70 W, concentrating the savings in the telecommunication system.

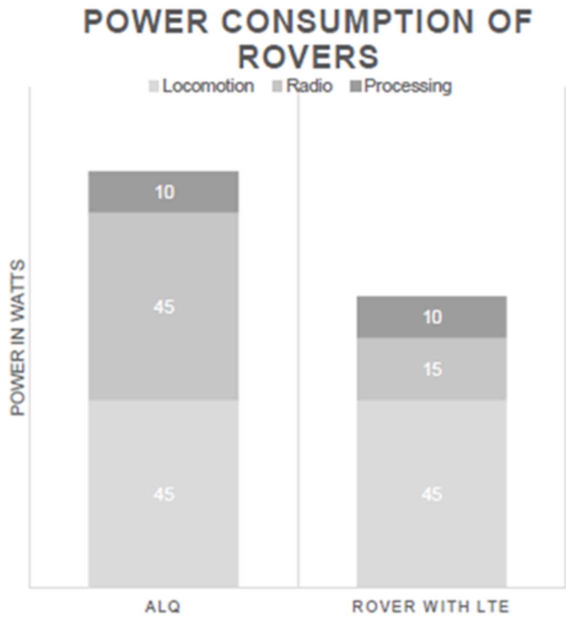

Figure 4.8. Power consumption of rovers. Credits: [11].

Before proceeding with the tests, it was necessary to analyze the potential requirements of the landing site. To evaluate the performance, it was essential to quickly have a signal propagation model that included the hypothesis of a variable terrain: the empirical models did not consider the inhomogeneity of the lunar surface, Heuristic knife-edge models underestimated the effects of hills and craters, the parabolic or integral numerical equations were too long to solve. To overcome this problem, a new rapid analytical model was developed, the calibration of which took place on the ground of an area considered as similar as possible to the lunar soil: the island of Fuerteventura, in the Canary Islands, Spain.

During the calibration campaign of the signal propagation model carried out on the island of Fuerteventura, some precautions were taken to replicate as faithfully as possible the conditions that the rovers would find on the lunar soil. The Audi Lunar Quattro were identified by a low-profile towing on which an antenna was installed one meter above the ground, it was kept in motion by a 4x4 vehicle. The Nokia – Small Cell base station antenna was placed at 4 meters high replicating its position at the intended landing site. After about five days of measurements and fine-tuning of the propagation model, a result was reached that allowed to simulate communication in the lunar environment.

Figure 4.9. Moon surface vs Fuerteventura's land. Credits: [11].

The graph at the top left shows the terrain profile of the proposed landing site indicating the reliefs and the distance from the place of interest marked as A17. The next two graphs show the variation in signal strength as it moves away from its emission source. The first in the upper right defines the coverage of the signal emitted by the base station allocated on the landing site, the second at the bottom defines the coverage of the signal transmitted by a rover near the place of observation of the remains of the Apollo 17 mission. The data represented about the maximum distance at which you can communicate, combined with the descent path and restrictions to protect the A17 site, are necessary for choosing the correct moon landing site [11].

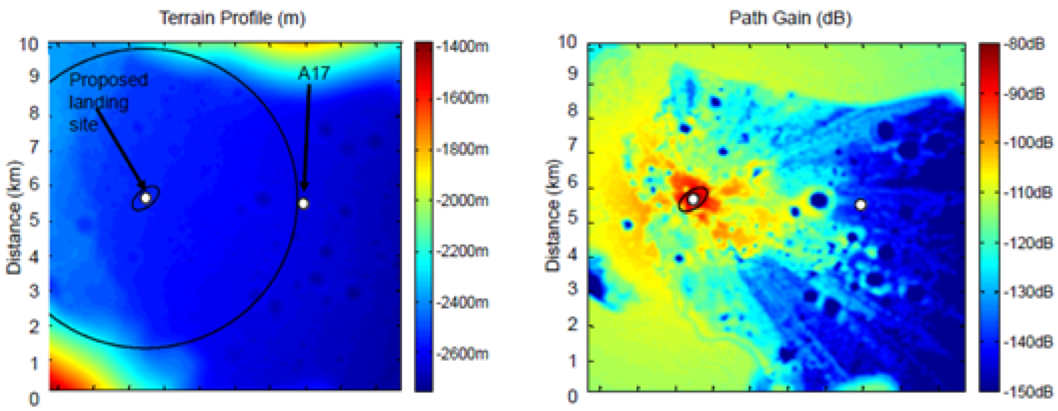

Figure 4.10. Terrain Profile graphic and Path gain from LTE base station at landing site. Credits: [11].

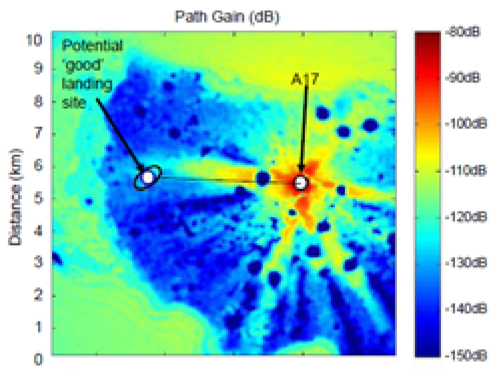

Figure 4.11. Path Gain from user equipment at A17 site. Credits: [11].

4.3 NASA-Artemis program

Figure 4.12. Artemis program. Credits: [21].

The new era of lunar exploration will be called Artemis, it will push the adventure in space beyond all scientific and technological limits once again, preparing the human species for the next big leap - the conquest of the planet Mars. The name is inspired by the Greek goddess Artemis, twin sister of Apollo and considered the personification of the crescent Moon.

Following the path outlined by the program, man will explore yet unknown lunar regions and will join people in search of the unknown. The desire expressed is to return to the moon with human presence, male and female, in the next three or four years (2024 – 2025) and build long-term settlements by the end of the current decade. Since the last astronaut set foot on the lunar soil, more than fifty years have passed and, in the meantime, man has developed increasingly advanced technologies and prepared himself for this step by living the last twenty years on board the International Space Station. It will take, however, several years in orbit and on the lunar surface before creating confidence with the operating environment for the construction of systems that support human life even far from planet Earth. Only then will we be able to embark to the red planet.

Figure 4.13. A snapshot of "firsts" to be achieved through the Artemis program. Credits: [21].

4.3.1 Scientific and technological objectives

The scientific objectives of the Artemis program have been set out in the priorities of the world's scientific community. The experiments that will be carried out in the lunar environment during the entire program will allow to study and understand, at least in part hopefully, the planetary processes and the historical impact of the Earth - Moon system. In addition, they will allow us to observe the universe from a new and unique point of view. The aspect that, however, will be most important for the future of human exploration will be represented by the possibility of investigating and understanding new possible risks for the human being during his extraplanetary activities, learning new methods to mitigate them. To be able to complete these tasks it will be necessary to use adequate scientific and technological instrumentation that will be transported on board the spacecrafts. Precisely about technology, new approaches and systems will be useful to be able to live with an extreme environment and to establish a sustainable human presence on the Moon. Among the main technological objectives there will be the fundamental ability of using the resources available on site, directly taken from the lunar soil, to avoid the huge transport of material from the planet Earth. The surface will offer two other major challenges: the need to ensure sufficient lighting for continuous electricity generation and the ability to mitigate the effects of lunar dust, highly abrasive and problematic for devices without adequate protection [21].

Figure 4.14. Lunar Surface Power unit overview. Credits: Artemis plan, NASA. Credits: [21].

In addition, the environment will present extreme temperature conditions and continuous exposure to radiation. Finally, it will be necessary to study a technology that allows the autonomous construction of structures and an access, positioning, and navigation service to better manage human-machine interaction.

4.3.2 Artemis I

During the first mission the Space Launch System rocket will launch an Orion capsule without crew members putting it into orbit around the Moon, where it will travel at least 40,000 miles before returning to Earth [21]. The main objectives of this flight test will be mainly two:

1. Demonstrate the performance of the SLS launcher.

2. Collect data on the re-entry of the Orion capsule, testing the protective shield on its return to the atmosphere, where it will face temperatures even above 5,000 degrees Fahrenheit before entering the Pacific Ocean.

Given the lack of crew, all those systems necessary for the support of human life will be removed in favor of useful tools to evaluate the performance of the modules.

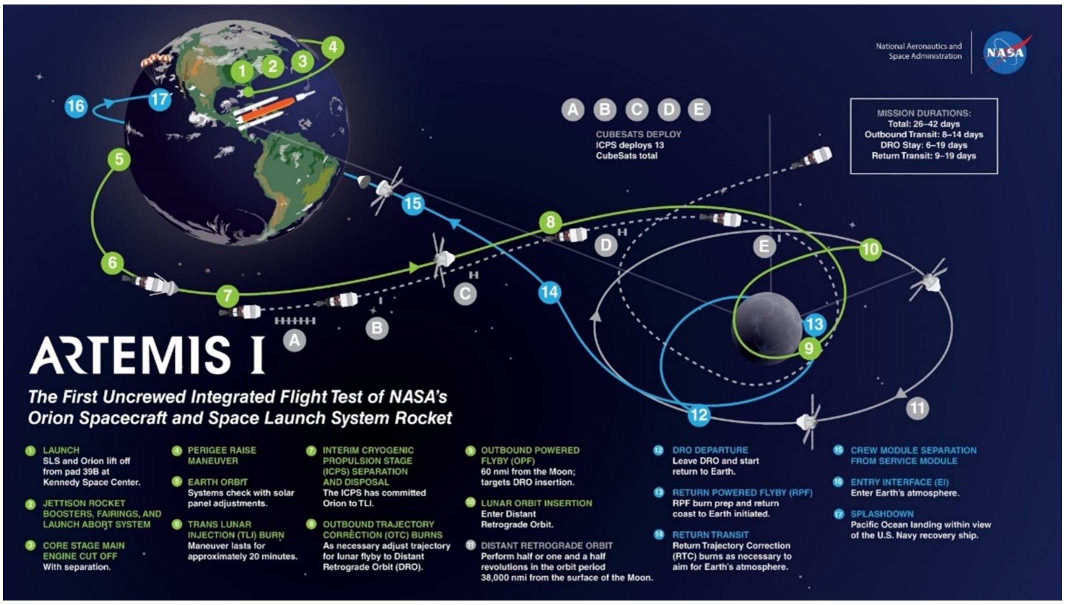

Figure 4.15. Artemis I flight plan. Credits: NASA.

This process will allow, among other things, to validate current predictive models for flight data.

Currently the development of the Orion capsule has been completed and the tests have already been brilliantly passed, including that related to the operation of the launch abort system shown in the figure.

The SLS rocket, on the other hand, is still in the assembly phase, after its engines have passed the ignition tests with a few months of delay. Despite this, the launch of the Artemis I mission remains scheduled for the fall of 2021.

In addition, to increase the safety levels of the first possible lunar landing, NASA seems interested in making the most of the program's first missions to carry out additional tests in orbit and on the Human Landing System (HLS) descent module.

As mentioned, it will be crucial to get results from the first Artemis missions. With the CLPS (Commercial Lunar Payloads Services) initiative, scientific payloads will be sent for the study of the lunar surface and the resources contained in it, especially near the polar area indicated as the base site. Then it will be the turn of the Rover VIPER (Volatile Investigating Polar Exploration Rover), built by Astrobotic of Pittsburgh, Pennsylvania, whose task will be to analyze the volatile elements present in the soil, such as water.

Figure 4.16. Space Launch System and Orion Crew Vehicle overview. Credits: [21].

Figure 4.17. A launch abort system with a test version of Orion attached soars upward on NASA's Ascent Abort-2 (AA-2) flight test atop a Northrop Grumman provided booster on July 2, 2019. Credits: [21].

In addition to these devices that will directly touch the lunar surface, the Artemis I mission will release into orbit 13 CubeSats deployed by the Space Launch System, five of which will provide data on the Moon and its environment while the others will conduct new technological demonstrations in deep space. The human exploration activity will begin with the crew aboard the Orion module during the Artemis II mission scheduled from 2023. During this time, further tests will be conducted in orbit on the moon landing systems from the hardware, software and wherever possible and necessary for the start of Artemis III starting in 2024.

Figure 4.18. Commercial Lunar Payload Services and Volatiles Investigating Polar Exploration Rover overview. Credits: [21].

4.3.3 Artemis II

The second mission of the program will finally bring with it the presence of man. Four astronauts will travel aboard the Orion capsule until they reach our satellite. The duration of the mission will be approximately ten days, during which a new record will be reached: they will be the humans who have traveled the furthest from the Earth's surface, going to the dark side of the Moon [21].

At launch, the SLS rocket will carry the crew to earth orbit. Before beginning the journey to the Moon, the spacecraft will make two orbits at increasing altitude around the Earth, the first on elliptical orbit between 115 and 1,800 miles, the second after a propulsive stage ignition between 200 and 59,000 miles with a travel time of about 42 hours. After reaching the High Earth Orbit (HEO) the Orion capsule will unsettle from the propulsive stage to begin to perform some demonstrations on the operations in the vicinity, carried out in manual control.

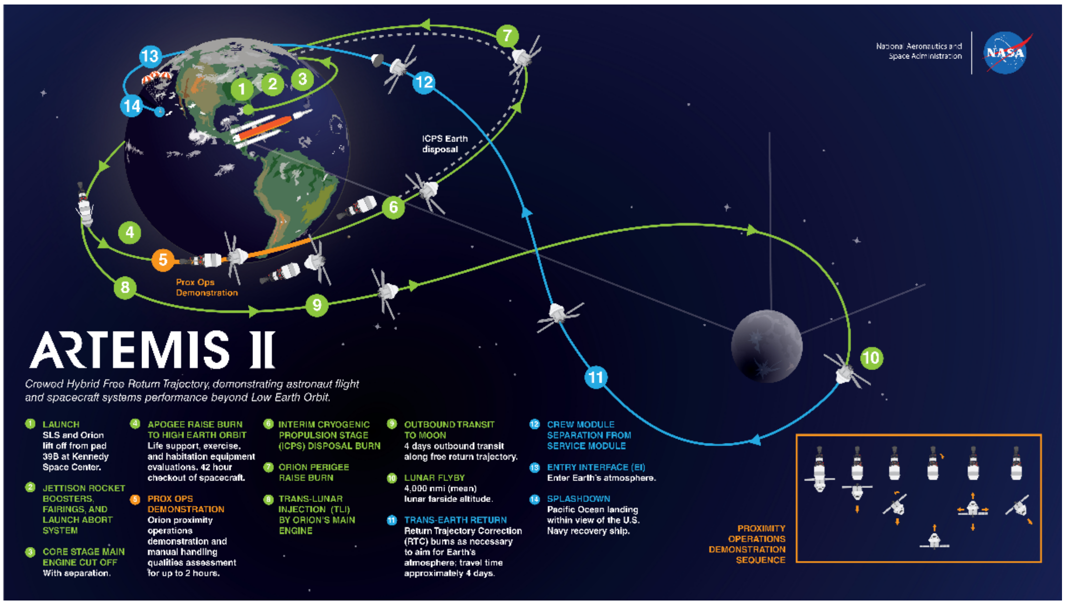

Figure 4.19. Artemis II flight plan. Credits: NASA.

The long orbital period will allow the verification of the operation of all life support systems and the possibility of removing the Orion Crew Survival System suits. In addition, at this distance the spacecraft will travel beyond the GPS navigation and TDRS communication systems, so it will be an excellent opportunity to test deep space communications with the Deep Space Network.

The last task of the propulsive stage will be to generate the necessary thrust for the Translunar Injection Maneuver (TLI), which will lead the crew to begin a 4-day journey to lunar orbit. After a fly-by around the Moon, Orion will be naturally attracted to Earth's gravity that will allow its return without the need for any propulsive maneuver.

Another key component for the success of a sustainable plan will be the Gateway, whose first two modules PPE (Power and Propulsion Element) and HALO (Habitation and Logistic Outpost) will be integrated and launched starting from 2023. From 2024 the Orion module will take the astronauts into orbit and the descent module will be able to dock directly to the capsule for their transfer from the first manned missions. A second option is represented by the possibility of docking directly at the Gateway, a scenario that will occur starting from subsequent missions. Once on the orbiting outpost the crew will be able to carry out scientific experiments and prepare for the moon landing, at which time it will dress the new xEMU spacesuits.

Figure 4.20. Deep Space Network overview. Credits: [21].

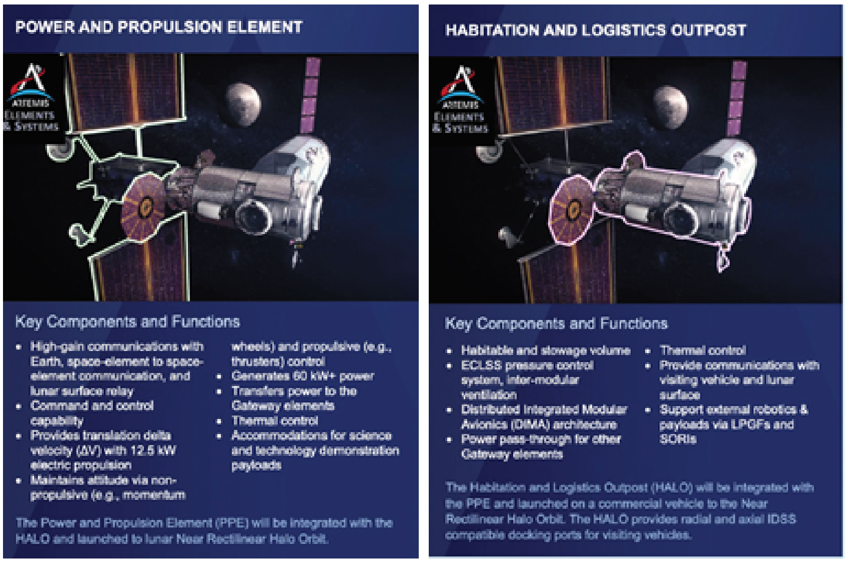

Figure 4.21. PPE and HALO Gateway Modules. Credits: [21].

The new spacesuits will allow a significant increase in spacewalks promising greater safety, a better fit, simplified maintenance operations and a more reliable communication system.

Figure 4.22. Artemis xEMU spacesuits. Credits: NASA.

4.3.4 Artemis III

Artemis III will be the culminating point of the numerous tests and more than two million miles accumulated in space by NASA's transport systems during previous missions [21]. Orion will again transport four astronauts to lunar orbit, where they will descend to the ground aboard the HLS.

For subsequent missions the Gateway will represent an important point of support that will allow the same crew to carry out even more than one descent on the lunar soil.

The exact landing site of the astronauts will depend on a multitude of factors, among which not negligible will be the final launch date of the mission. The US space agency is working on the choice of one or more locations that meet certain requirements, based on data collected by the Lunar Reconnaissance Orbit (LRO):

1. Significant solar lighting to power energy production devices.

2. Minimum temperature range.

3. Continue line of sight with Earth for mission support communications.

4. Proximity to permanently shaded areas, possible places of containment of ice water.

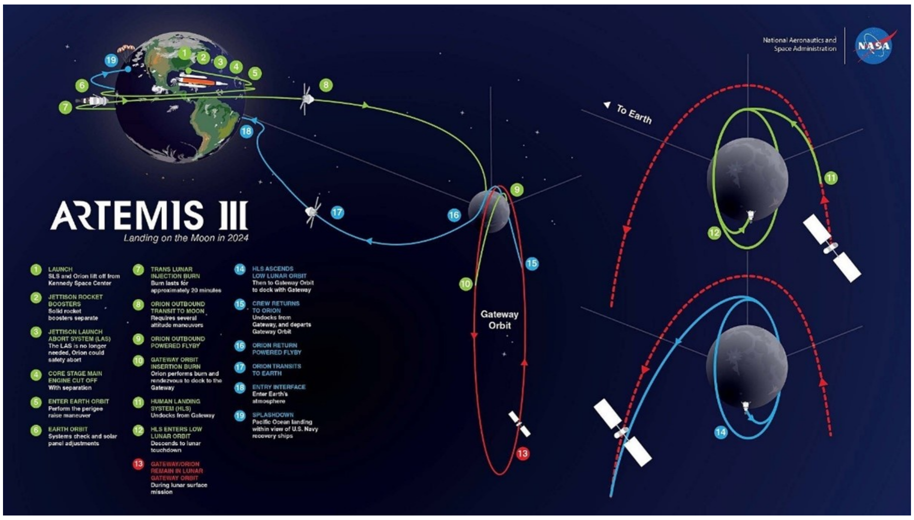

Figure 4.23. Artemis III flight plan. Credits: NASA.

Figure 4.24. Human Landing System overview. Credits: [21].

Artemis base camp will likely be set up near the South Pole to support longer-lasting surface expeditions. It will include Lunar Terrain Vehicle (LTV), a pressurized housing module and power generators, as well as systems that allow the use of local resources.

Figure 4.25. Artist's concept of the Artemis Base Camp. Credits: [21].

Figure 4.26. Lunar Terrain Vehicle and Habitable Mobility Platform overview. Credits: [21].

Once on the lunar surface, astronauts will be able to conduct new scientific experiments, also taking advantage of the load capacity of the HLS to transport some payloads. In the first week it is planned to collect some samples useful for the research that will be conducted on Earth. At this first moment the crew will live on board the descent module. The planned outputs will range from a minimum of two EVA to a maximum of five and will be able to count on the use of the pressurized Lunar Terrain Vehicle and on a non-pressurized rover for travel at great distances from the base camp.

4.3.5 Preparing for Mars

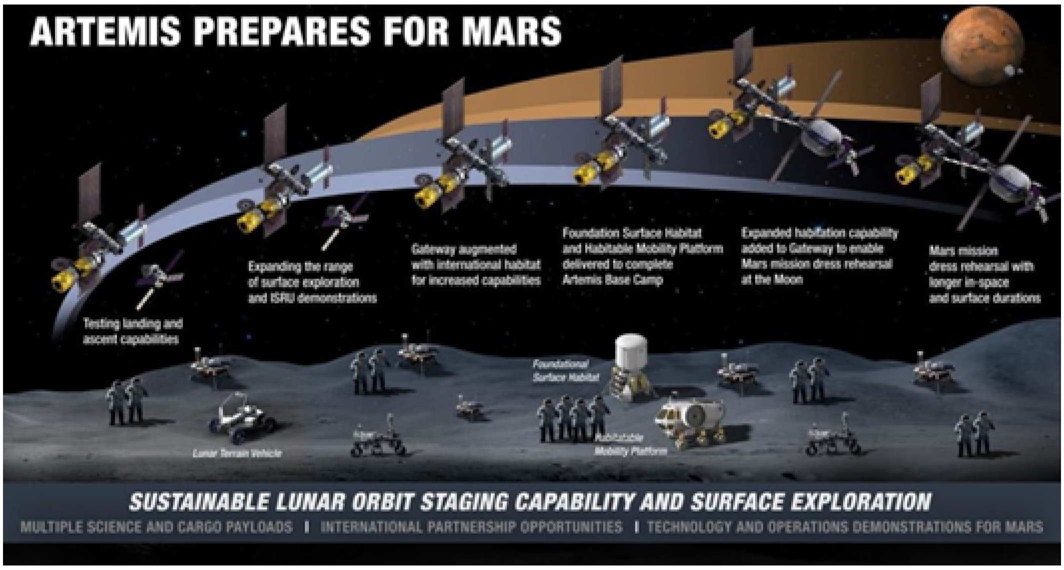

Figure 4.27. Artemis prepares for Mars. Credits: [21].

After Artemis III will begin a series of studies and missions in orbit and on the lunar surface with the aim of preparing man for Mars. Gateway capabilities will be improved, Artemis base camp at the South Pole will increase its size and will always ensure new services that will help achieve a sustainable condition for exploration. The network of infrastructures that will guarantee communications, increasing their performance and the services offered, will be added, and expanded. The additional facilities will allow the base camp to also support expeditions lasting one or two months on the surface, allowing to carry out studies also from the biological point of view on the response of the human body to prolonged exposure to the space environment in a place so far from the Earth.

Figure 4.28. Human Research Program. Credits: NASA.

Chapter 5

5G Use cases in Artemis program

Communications will be one of the crucial components within the Artemis program and the use of 4G/LTE technology and, subsequently, 5G promises to revolutionize communications on the lunar surface by bringing reliable and high data rate connections but containing cost size and power required.

In October 2019 Nokia was appointed by NASA as a partner for the development of this aspect, demonstrating that it has confidence in the work previously undertaken by the company within PTS's Mission to the Moon program. By the end of 2022, the telecommunications company expects to be able to propose an end-to-end solution, ultra-compact and ready for the space environment. For this initial development mission Nokia will work together with Intuitive Machines for the integration of its devices on board some lunar landers and rovers. Once the landing is complete, the system will configure itself and stability the first LTE connection on the Moon. In an internal interview Marcus Weldon, Chief Technology Officer at Nokia and Nokia Bell Labs President explained what equipment they will use to achieve the intended purpose [23]:

"Nokia's lunar network consists of an LTE Base Station with integrated Evolved Packet Core functionalities, LTE User Equipment, RF antennas and high-reliability operations and maintenance control software. "

The LTE base station will be mounted on the lander along with a passive antenna system, while the LTE user equipment will be mounted along with an omnidirectional antenna on a rover, or some payload deployed once it has touched the ground.

The main objectives will be two: to test the communications between the lander and the rover at short range, a few hundred meters, and at a wide range, two or three kilometers away.

Obviously, everything will be produced trying to overcome the critical issues highlighted at the beginning of the previous chapter.

In the fifth chapter, the expected use cases for 5G technology will be presented in detail. It will be a key part of telecommunications management and the Artemis program has three precise and possible scenarios in mind:

1. The implementation on board the Lunar Gateway, outpost orbiting the Moon.
2. The creation of a constellation of satellites for the management of networking, positioning, navigation, and scientific utilization services, called LUNANET.
3. The management of communications on the lunar surface within the Moon Village.

5.1 Lunar Gateway

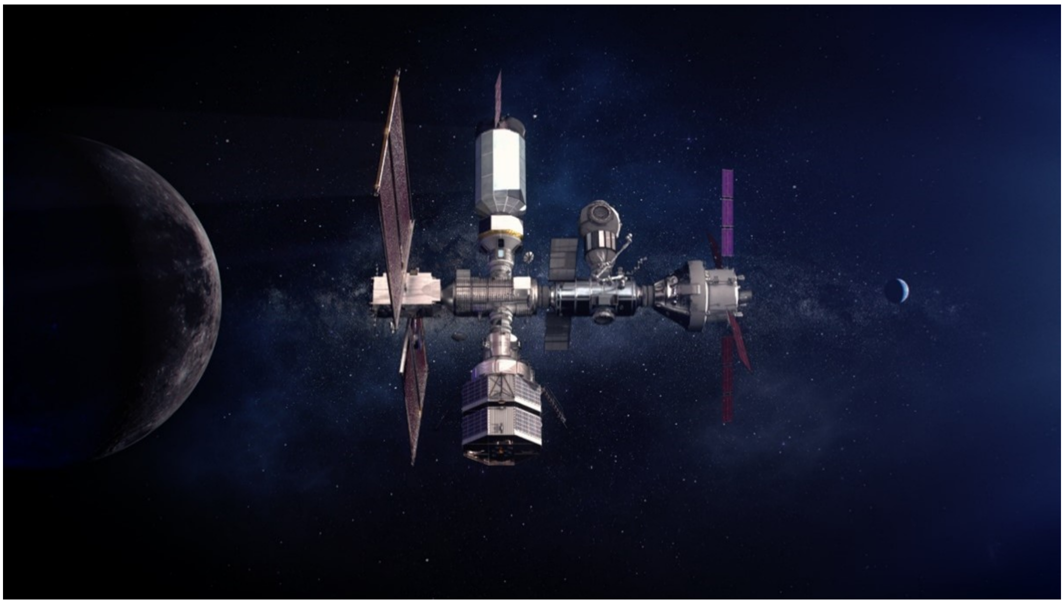

Figure 5.1. Gateway's concept. Credits: NASA

The Lunar Gateway will represent the first human artifact inhabited in orbit around a celestial body other than the Earth and in the future can be recognized as a crossroads for the exploration of the solar system. As anticipated, the construction of the orbiting lunar outpost will begin from 2023 with the Power and Propulsion Module (PPE) and the Housing Module (HALO) and will involve numerous space agencies: NASA (USA), ESA (EU), JAXA (Japan), CSA (Canada). The composition will only take place once the modules have reached operational orbit, a Near Rectilinear Halo Orbit (NRHO) around the Moon. The outpost will perform the fundamental task of welcoming and providing life support to astronauts arriving from planet Earth. Once fully operational, after disembarking from the Orion capsule, there will be a period of acclimatization and preparation for missions on the lunar soil. The Gateway will not only be a transit point for human exploration, but once in operational orbit it will also allow scientific experiments to be carried out in deep space, beyond the Van Allen belt. The main topics attracting attention are radiation, heliophysics and space weather.

5.1.1 Gateway's orbit

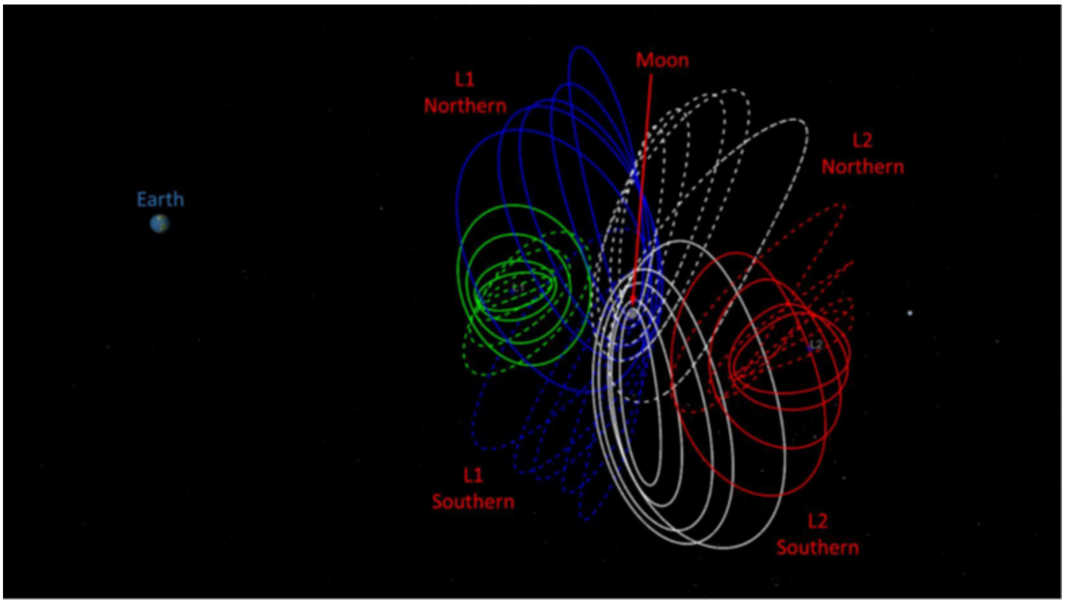

Figure 5.2. Halo Orbit Families. Credits: [16].

The Gateway program selected a Near Rectilinear Halo Orbit (NRHO) of the southern family L2 as its operational orbit.

indent NRHO are subclasses of HALO orbits, orbits with properties that exist only in a three-body system, two of which are characterize by gravitational attraction forces (Earth, Moon, Gateway). HALO orbits are associated with the three collinear libration points of the system, but interest in this scenario is limited to those near the L1 and L2 points. Of course, there are both families of orbits to the north and south of the lunar orbital plane.

This type of orbit was chosen because it represents an advantage for the variety of possible missions that can be implemented by the Lunar Gateway. It has a low orbital maintenance cost and offers access to the surface with a short journey lasting just half a day. Cargoes can reach it with trajectories with very low delta V required and, in addition, could represent an excellent starting point for interplanetary destinations. Finally, they can provide extended communication periods in terms of coverage with one of the two lunar poles, with very short blackout periods: about 3-4 hours every seven days [16].

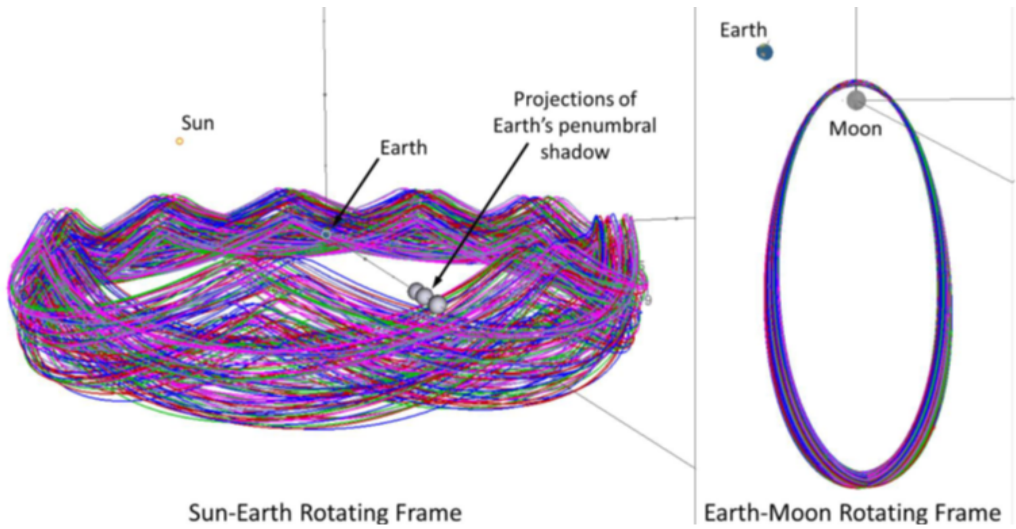

Figure 5.3. 15 Year NRHO Reference Trajectory. The figure on the left shows the trajectory in the Earth-centered Sun-Earth rotating frame, illustrating the 9:2 LSR pattern for eclipse avoidance. The figure on the right shows the trajectory in the familiar Moon-centered Earth-Moon rotating frame. Credits: [16].

The final choice followed several criteria:

1. An orbit around L2 was chosen to have better coverage of the far side of the Moon.

2. Among the available families, the southern were opted for as they provide excellent coverage of the communications of the lunar South Pole, current areas of interest for the exploration of the Moon. In addition, it offers the possibility of maintaining the orbit with maneuvers that require a smaller delta V, about 1.86 mm/s per revolution.

3. It allows to decrease the periods of eclipse due to the position of the Earth and the Moon. The first manage to be avoided altogether except for two

occasions during the fourteenth and fifteenth year of planned activity (2034-2035), the second will instead be frequent, but with a maximum duration of 80 minutes, well below the limit bearable by the instrumentation equal to about 150 minutes.

The resulting orbit has a perilune radius varying between 3196 and 3557 km and an apollonian range between 55,000 and 70,000 km. The average orbital period is 6.5 days.

The reference trajectory for the Gateway is captured in an SPK-like kernel compatible with the SPICE ephemeris system created at NASA's Jet Propulsion Laboratory (JPL). The complete kernel of the studied trajectory is available on the JPL website.

5.1.2 Italian contribution

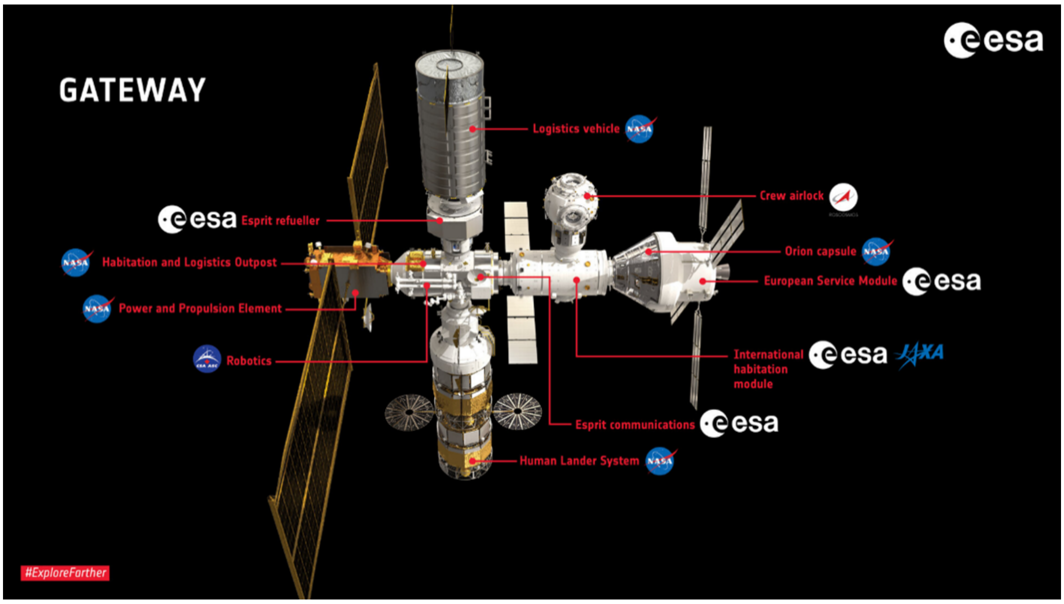

Figure 5.4. Gateway's concept. Credits: ESA.

Thanks to the partnership with the European Space Agency (ESA), the Italian company Thales Alenia Space born from the union between Thales (67%) and Leonardo (33%) will take care of the development of two modules of the Lunar Orbital Platform – Gateway (LOP – G): the International Habitat module (I – HAB) and the ESPRIT communications and refueling module:

1. I – HAB, pressurized module that will contain the housing for the crew and some docking doors for refueling vehicles and resources. Among the elements that will be improved, compared to the current ISS, there will be lighter structures, optimized micrometeoroid protection and thermal control systems and innovative air conditioning systems. Its exposure to the radiative environment of deep space will offer the possibility to study and test new possible designs. Finally, we will try to make the stay better for the occupants. The launch date is scheduled for 2026.

2. ESPRIT, the module will consist of two parts. A first part will be the active refueling module that will provide Xenon and chemical propellants for the purpose of extending the life of the Gateway. The second part will include the HCLS (Halo Lunar Communication System), which will manage communications between the Gateway and the Earth or the lunar surface. Its launch is scheduled for 2024.

5.1.3 Communication with Earth

One of the key points in the design of an interplanetary outpost is the communication channel with the Earth. It will have to make it possible for 5G communications terminals to access terrestrial network services and ensure a high data rate and accessibility, to meet the requirements at an early stage and in the future. For this scenario, optical communications are currently being studied on board the ISS and two possible configurations have been planned [17].

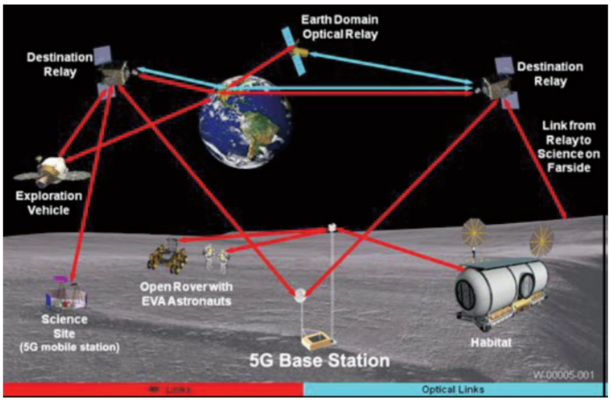

Figure 5.5. Example of possible 5G communication network with backhauling to Earth realized by means Moon Orbiter. Credits: [17].

This first vision examines the use of some satellites placed in stable orbits around the Moon that retrains transmit traffic directly to the Earth station or to an additional node, hypothetically the Lunar Gateway, placed an in a Halo orbit around a Lagrangian point of the Earth - Moon system. One of the greatest difficulties of this solution would be given by the need to put into lunar orbit a constellation of satellites, counting that the possible stable orbits are few near the Moon.

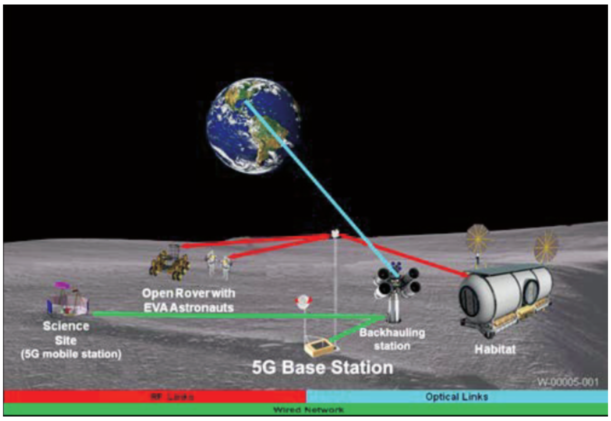

Figure 5.6. Example of possible 5G communication network with backhauling to Earth realized by of direct-to-Earth optical link Credits: [17].

The second vision examines the possibility of using a direct link between the lunar and earth's surfaces.

In this case the different 5G base stations would be connected by cable to optical backhauling stations such as the Lunar Laser Ground Terminal (LLGT), already adopted for some demonstrations with the Lunar Laser and Dust Environment Explorer (LADEE). This proposal is easier to design and develop, but the noise temperature of the planet could significantly degrade the achievable performance. However, the Gateway will also have communication channels with Earth for its management and monitoring of its facility. A direct link will therefore be present and will use the antennas of NASA's Deep Space Network to transmit and receive information.

5.2 LunaNet

Nasa's extensible and scalable lunar navigation and communication system as an integral part of the Artemis project is called LunaNet [15].

Unlike traditional space communications and navigation services, LunaNet will bring more dynamic operations centered on the fundamental characteristics of a communications network. While the terrestrial internet hides its complexities through the development of an Internet Protocol, in space some limitations do not allow its use for solutions such as LunaNet or other distant destinations in the solar system. The goal remains, however, to provide a service to the user without the need for him to know special procedures; this will be achieved using the Delay/Disruption Tolerant Networking Bundle Protocol. These protocols contain information about the source, destination of the message and the urgency of delivery, all useful information for the management of communications and the allocation of available resources.

The network architecture will be based on nodes, access points to the network, capable of providing mainly three essential services to lunar explorers:

1. Networking services, for transferring data between nodes in single or multi-node channels with an end-to-end path.
2. Positioning, Navigation & Timing services, for the determination of position, speed, and temporal synchronization. Also useful for the implementation of Search and Rescue (SAR) services.
3. Science utilization services, for the ability to send scientific alarms and measurements useful for human safety and protection, as well as to support the management of payloads and scientific activities.

In addition to these aspects, LunaNet has two other fundamental characteristics: the ability to improve and extend the architecture over time following the evolution of mission requirements and concepts, the possibility of re-proposing the architectural approach to any celestial body present in the solar system to create a real space internet service.

LunaNet will not only be a communications facility related to the Artemis program, but any lunar mission can also be part of the infrastructure, be a user or even fill both roles. Any spacecraft can safely conduct its missions and achieve its objectives while acting as a reference node for the LunaNet.

The various network access nodes can be connected to each other to provide an end-to-end path. The image above shows an example of an architecture that identifies the path followed by the information during a communication between user A and user B. In this specific case, the ability of the nodes to retransmit the received signal is exploited, which uses only the networking service, to allow communication even at a great distance.

5.2.1 Networking service

LunaNet will provide network-based communications capable of multi-hop store and forward data delivery. Access to this service will be possible from the lunar

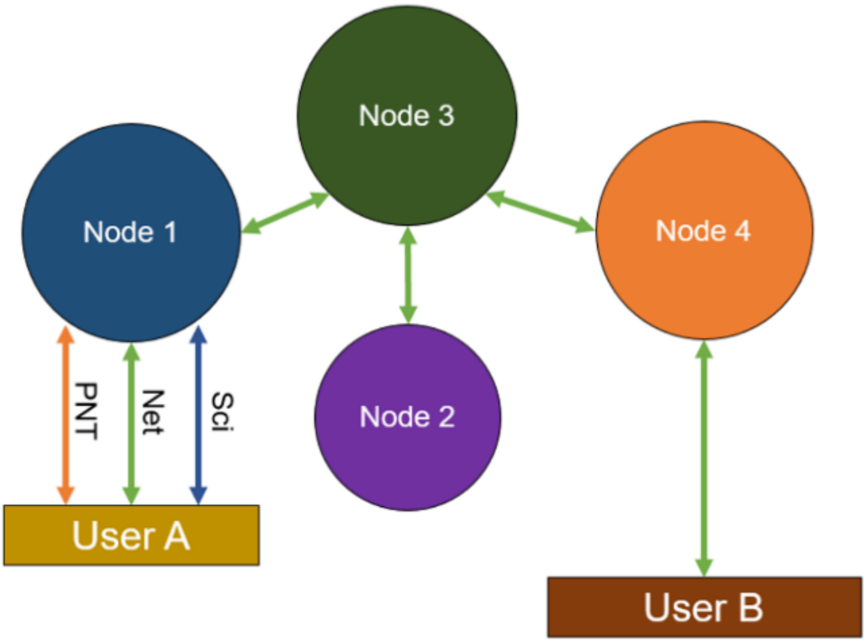

Figure 5.7. User A receives networking, PNT, and Science Services through Node 1 and can Communicate with User B through LunaNet. Credits: [14].

surface either from an orbiting terminal or directly located on Earth. In addition, the performance offered will allow such high data rates that you can share live video in high definition. The communication service can be offered at different levels, it will take advantage of the standardization of the network to improve interoperability between adjacent nodes regardless of the infrastructures that will represent them. Finally, the transmitted data will meet certain security requirements such as confidentiality, integrity, and availability. The two types of links will be:

1. Proximity Links or Forward and Return Links, which will connect users to the network for sending or receiving data.

2. Network-to-Network Trunk links, for the connection between two nodes of the network.

5.2.2 PNT-Positioning, Navigation and Timing

The PNT service will allow relative autonomous navigation on the surface and the possibility of locating any device connected to the network that is around competence. In addition, the deployment service of a reference time will help all those

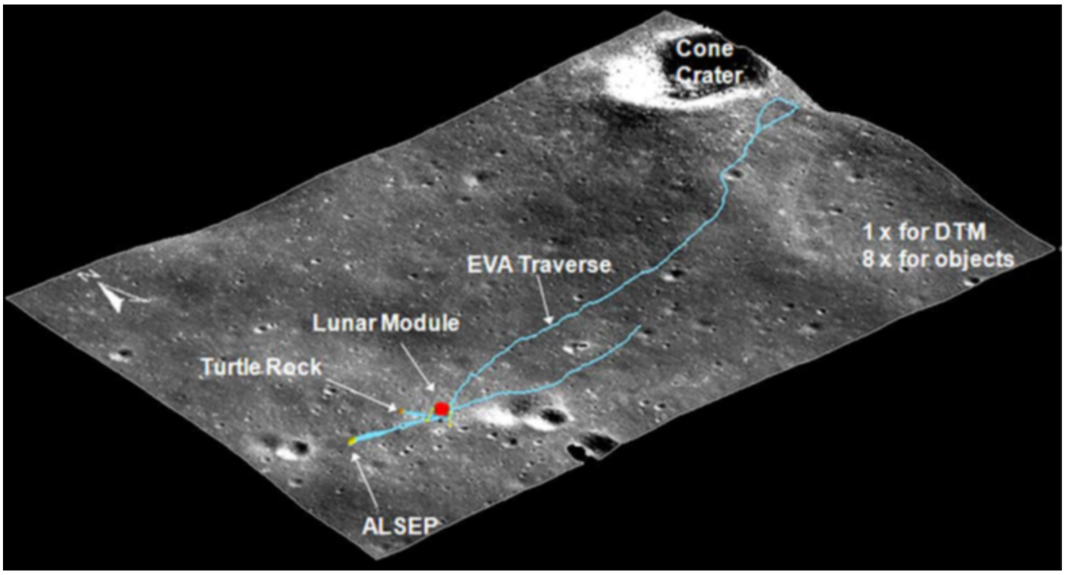

Figure 5.8. EVA's path. Credits: [15].

operations that need synchronization with each other.

In recent years, several approaches have been attempted, from the weak high-altitude signal of the Global Navigation Satellite Systems (GNSS) to the Terrain Relative Navigation. ESA released in 2008 two feasibility studies on a planetary navigation system based on the use of COTS components, based on the IEEE 802.16 WiMAX standard, which met the requirements for a short-range service. Over 8 kilometers the performance and coverage of this type of communication architecture did not produce satisfactory results. It remains, therefore, a critical aspect that must necessarily meet the demands of users in terms of safety and situation awareness. Being able to improve the accuracy of the results obtained would be fundamental for the reduction of false alarms due to possible collisions. To meet mission requirements, satellites use an onboard orbit determination technique using flight –qualified hardware and software. To ensure a high level of reliability, a similar type of architecture in the lunar environment must be able to rely on one or more of these elements:

1. A reference source of time and stable frequency, which guarantees a signal that allows the synchronization of devices. These services are referred to as timekeeping and time distribution.

2. GNSS signals, at least four signals at once. Unfortunately, this occurs with limited availability in the lunar environment, but the measurements obtained can still be processed on board in sequence for an estimate of the current

orbital state and fused together to have a robust set of measurements.

3. Angular measurements useful for defining the horizon plane.

4. Images of the surface of the celestial body for a ”visible” navigation. The images allow you to visualize craters, valleys and other distinctive features that can help in the use of a relative navigation technique on the lunar soil.

An even better solution would involve the simultaneous use of at least two of the previous sources, to diversify and redundant the measurements. A series of different measures allows to validate and verify the data reducing the effects of anomalies.

5G technology is expected to be of paramount importance for achieving the required performance and enabling the PNT service. The 5G standard will allow to support communications and different applications, including positioning services that will depend heavily on the distribution of the cells that will cover the lunar site. In the case of short-range services, it will be possible to take advantage of the maximum use of MIMO devices for a location based on the angle of arrival of the signal. For a long-range service, the measurement will have to take place on several cells and must be combined with inertial measurements and the time of arrival of the signal. The measurement of a time interval returns to have as a pivotal point the need to have a reference time for the synchronization of devices. As previously mentioned, this task on Earth is carried out thanks to the use of the GNSS constellation, while as far as the lunar surface is concerned, we will try to exploit the same type of approach for the use of 5G Base Stations. The critical factors identified are the strength of the signal, its dynamism, and the geometry regarding the arrangement of satellites. The same studies mentioned above show that it is sufficient for use in the lunar transfer orbit, for low lunar orbits and during the phases of descent and movement on the lunar soil. For this purpose, it will be enough to design an antenna capable of tracking the GNSS signal directly from the lunar surface: cost expectations are around 50,000 euros and the minimum performances provide for a passive gain of at least 13dBi; factors that do not preclude its realization. The proposed approach will provide base stations with the necessary synchronization also using a professional high sensitivity timing GNSS receiver configured in timing mode. The accuracy potentially achievable by this system is estimated to be in the order of 50-100 meters with a delay of one microsecond or less, acceptable values for the synchronization of 5G / LTE base stations.

5.2.3 Science utilization service

The scientific use service will allow to carry out important scientific observations, regarding the Sun and the Heliosphere allowing to receive timely warnings in case of solar events in progress. The use of an X-ray and Solar Energetic Particle (SEP) monitoring system will ensure to evaluate the emission of X-rays after a time of about 8 – 10 minutes from the solar eruption allowing astronauts to take the necessary precautions before the arrival of the SEP wave, expected about 200 minutes from the beginning of the solar event. High-energy Solar particles are part of space weather and one of the greatest dangers for manned missions.

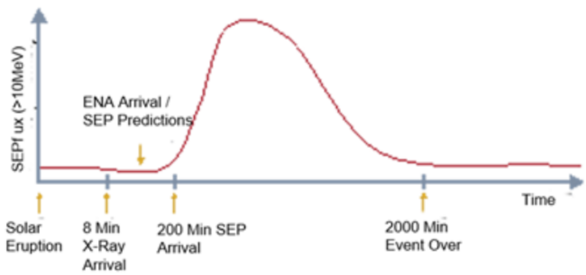

Figure 5.9. Event Timeline to which the Crew On board a Deep Space Vehicle Must Respond. Credits: [15].

5.2.4 LunaNet architecture

For this type of communication structure, different configurations are currently being studied.

Depending on the option chosen, each satellite can be directly in contact with the Earth and with the terminals on the lunar surface, or it will also present the possibility of exploiting crosslinks with the other elements of the constellation to reach a terminal at any time, even if not currently in line of sight. Other options involve the use of a single relay in contact with the Earth, whether it is orbiting or on the lunar soil. The gateway could be one of the elements suitable to cover this role, keeping in contact Earth and satellites belonging to LunaNet. As with the terrestrial internet connection, there are different ways to configure the infrastructure, and it can reach the form necessary to follow the evolution of the elements that compose it.

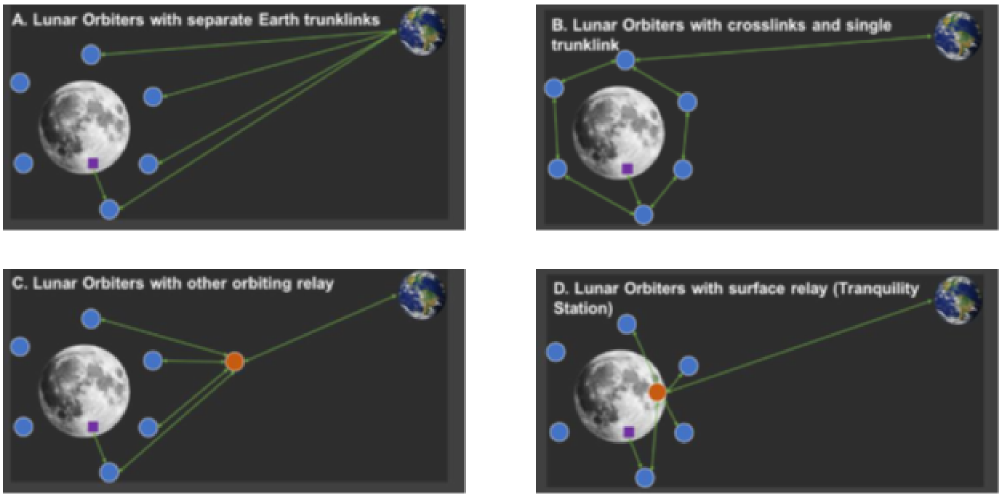

Figure 5.10. LunaNet Instantiation Examples. Credits: [15].

Figure 5.11. Moon Village Logo. Credits: [7].

5.3 Moon Village

The Moon Village will represent a very complex system, expandable and open to integration with the other elements of the planned and future missions [7]. One of the fundamental aspects on which its architecture will be based is that of communication management. The network that will keep connected all the elements that will make up the village will exploit 5G technology and will be designed in accordance with the requirements for robotic or human activities. To better understand its functions and the constraints to be respected to allow its construction and operation, ESA conducted a concept study for the architecture, design of housing modules and urban and engineering planning of the village. A summary of the design will then be proposed during the study phase, before focusing on the communications aspect.

5.3.1 Design requirement and drivers

Figure 5.12. Renderings of potential lunar village. Credits: Skidmore, Owings & Merril.

From the point of view of habitability, the structures must be able to accommodate a crew of four people for a mission duration of up to 500 days, revised to a maximum of 300 days after an assessment of the maximum limit of radiation exposure. In this regard, one of the main features will be the ability to sufficiently protect the crew from the radiation to which it will be exposed once on the ground. The housing module will also have to support scientific and surface activities, taking care of access to and from the lunar surface. The estimated lifespan for the facility must be at least 10 years. In addition to the tasks it will perform once on the ground, the module must be compatible with current launchers and be able to withstand the orbital trip to the Moon. Inside it will already mount a series of equipment that guarantee its habitability.

Currently the way in which it will be transported is being studied, NASA's Space Launch System does not seem able to bring a full housing module into orbit, so other options are under consideration, including the use of the newborn Starship of the SpaceX company.

For the realization of this concept, some assumptions have been made that became necessary after the results obtained from previous studies:

1. A unique architecture, which allows the exploration of the surface and the use of the resources present.
2. A village located at the lunar South Pole, near the rim of the crater Shackleton and in a permanently shaded region.
3. Replenishment arriving annually after the establishment of the first crew.
4. Continuous delivery of housing modules, cargo, and equipment for the expansion of the village.
5. Security measures to accommodate the human presence for a long time.
6. Ability to use in situ resources (ISRU) for reinforcement and construction.

Below are various concepts of the entire village or some fundamental sections such as housing and resource exploitation.

5.3.2 Habitat module

The proposed housing modules present a solution that develops vertically around a central rigid structure. Outside a multilayer shell that covers the structure once unfolded. The structure contains four habitable levels, separated by fixed or removable floors, which will contain areas suitable for the stay of the astronauts, the preparation of meals and many work sections with laboratories on board. The presence of a space dedicated to the preparation of EVA and the command center will also be fundamental. Obviously, there will be areas related to the health of astronauts, such as a place used as an infirmary and an area for physical exercise. In the lunar environment it will be essential to keep in training given the presence of a gravitational force, although about equal to one sixth of the Earth's.
indent

Below are some concepts related to the interiors of the housing module. In particular, the two images refer to a relaxation area for explorers and an area of laboratories and payload stations.

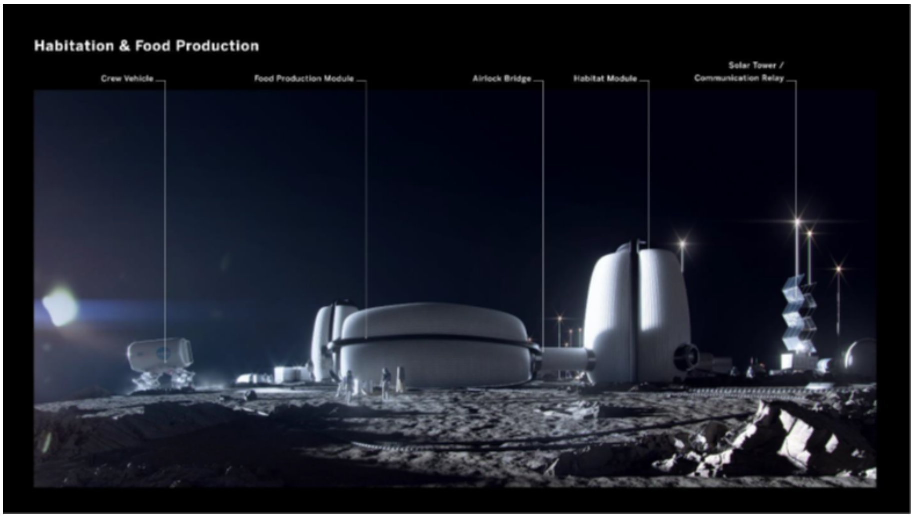

Figure 5.13. Various renderings of potential moon village. Credits: [7].

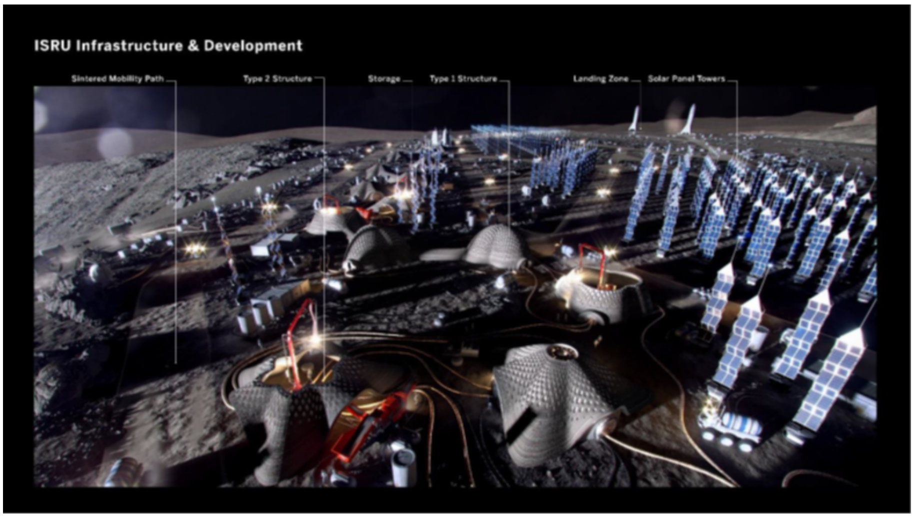

Figure 5.14. Various renderings of potential moon village. Credits: [7].

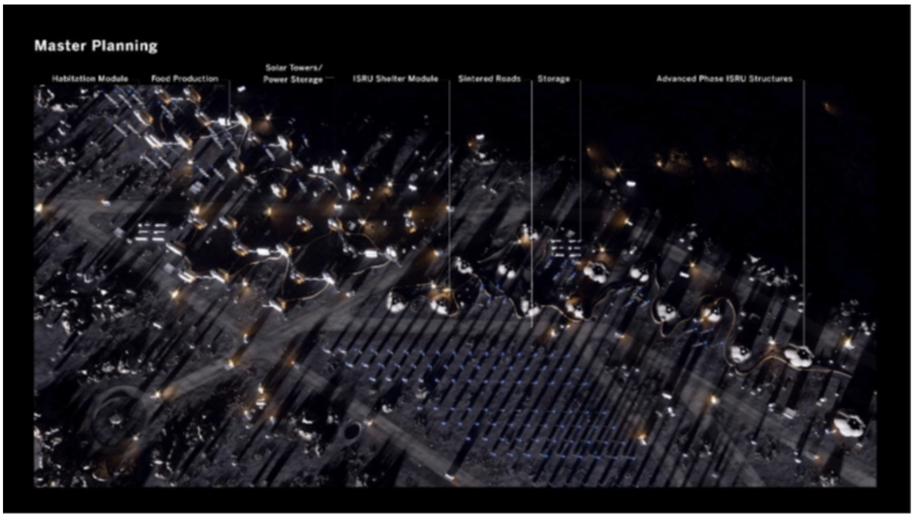

Figure 5.15. Various renderings of potential moon village. Credits: [7].

Figure 5.16. Internal of crew system concept. Credits: [7].

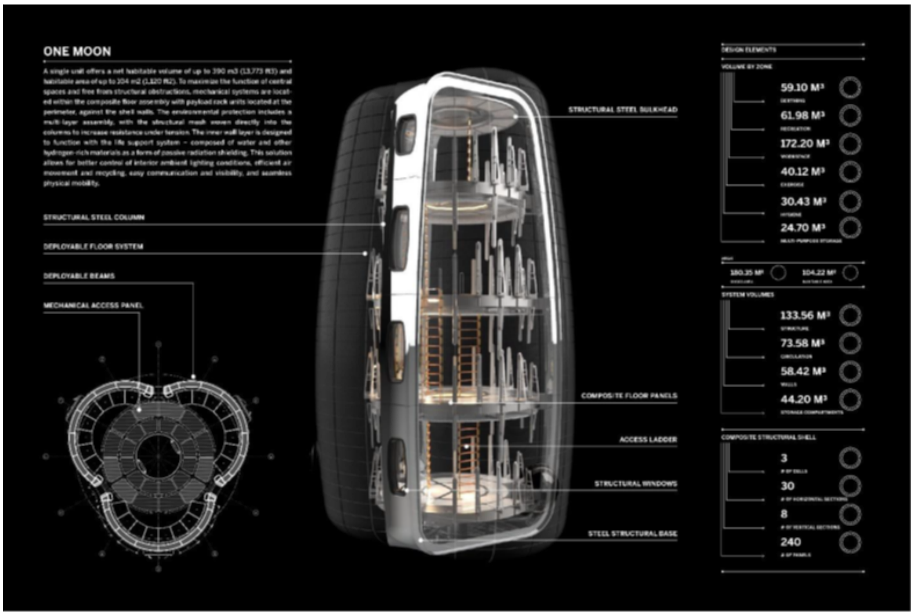

Figure 5.17. Habitat in x-ray view. Credits: [7].

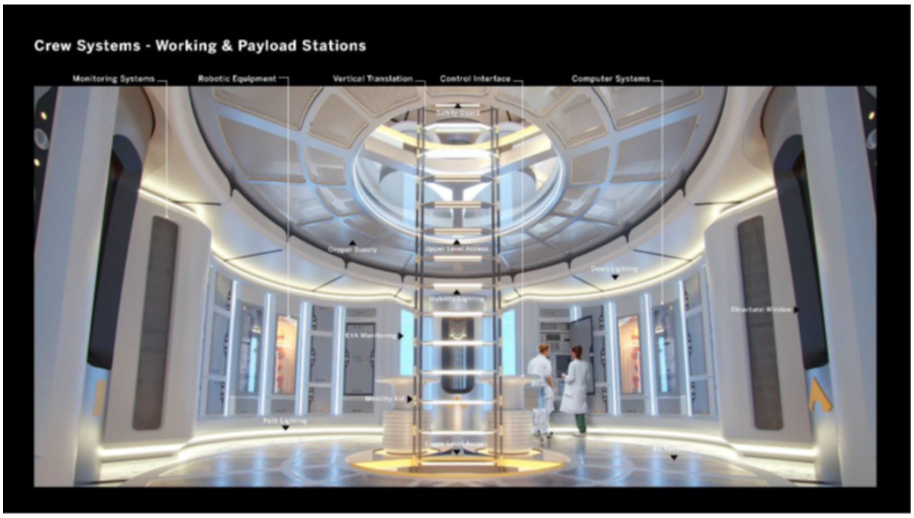

Figure 5.18. Internal of crew system concept. Credits: [7].

Chapter 6

Lunar surface network design process

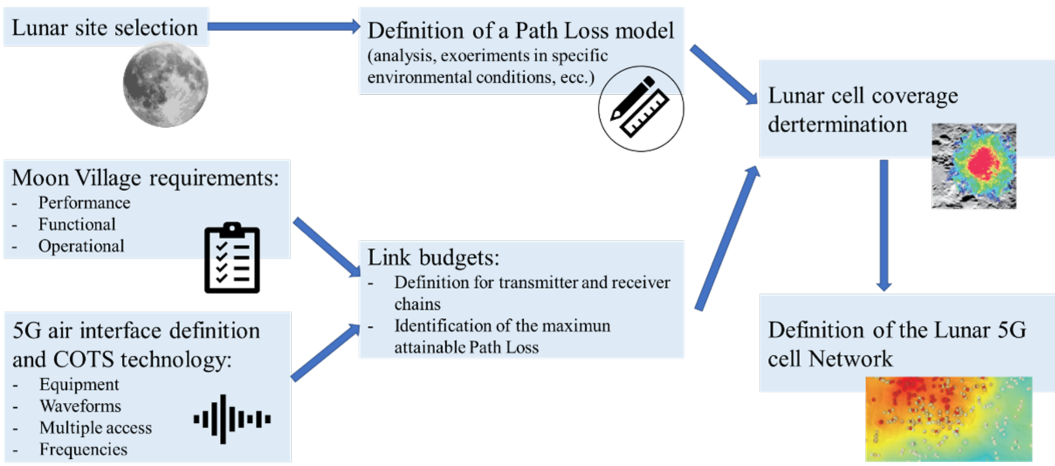

Figure 6.1. Logical steps for the design of the Lunar 5G network. Credits: [9].

The sixth chapter of the thesis aims to present a proposal for a logical process to be followed for the creation of a scalable network on the lunar surface based on the use of COTS components. [9] The ability to fully exploit the technology already developed in the terrestrial environment should allow to streamline the process of design and development of terminals designed specifically for an interplanetary outpost. Following this type of approach, the focus will be on the distribution of communication cells on the lunar soil. To do this, it will be necessary to make a reliable assessment of the maximum size of the individual cell before it can be possible to study the distribution of equipment. The factors that will affect the coverage guaranteed by a single element will be multiple and linked to different aspects. The operational, functional and performance requirements that the network will have to meet, in this case linked to the needs of the Moon Village and the site chosen for its location, will be the master together with the features that the 5G air interface can offer. The simultaneous evaluation of these two aspects will allow to create a link budget for the transmission and reception chains, and to calculate the maximum sustainable path losses from the communication channel. At the same time, after defining the place chosen for the construction of the village, the physical and environmental properties of the site will be evaluated to arrive at the definition of a model of path losses for the selected area. Once the link budget and the loss model have been completed and validated, it will be possible to determine the coverage guaranteed by a single cell and, iteratively, to the distribution that can provide better performance. Different instruments and different antenna placements will be evaluated to arrive at the solution. Obviously, with the advance of time the process and the configuration of the infrastructures can be expanded and evolved.

Currently some of the activities described above are already well underway and are producing the first results. ESA has conducted and published several studies regarding the selection of possible sites for the construction of the lunar village and, after evaluating some determining factors in the choice such as lighting periods and soil composition, has taken into account areas around the Shackleton and De Gerlache craters, located at the lunar South Pole. Added to this are some researches that have led to the definition of different models of path losses on an irregular terrain such as lunar soil.

6.1 Lunar site selection

For a careful analysis and evaluation of the possible sites indicated for the realization of the Moon Village project, it is necessary to define some key parameters that will act as selection criteria for the most suitable area. Before that, we must not forget the objectives of the current project: the containment of development costs (about 5 – 10 billion dollars), the operations expected by the end of 2024 and the economic sustainability of the structure, which allows it to grow exponentially.

Among the most important influencing factors identified to date it is worth mentioning the availability of power, linked to the hours of solar lighting, the possibility of implementing low-cost communications in large areas, the presence of water, hydrogen-based molecules, or other resources useful for construction and surface mobility.

6.1.1 Energy

From an energy point of view, it is crucial to carry out an evaluation of the hours of light available on the lunar surface, as they represent the only valid alternative to the use of nuclear technology to produce electricity. The period taken as a reference is the lunar synodic month, or the time elapsed before the Moon finds itself in the same position in the sky with respect to the Sun. It is comparable to about 29.5 earth days, 708 hours of which 354 at night. In any non-polar region, the challenge is twofold, as it is necessary to produce energy during the hours of light and at the same time store it also for the night periods. A study conducted and published by Dennis Wingo, CEO of aerospace company SkyCorp, carried out an analysis of the power available at polar, North, and South, and non-polar sites [29].

Lunar Development Power Worksheet	**Nonpolar**	**N Pole**	**N Pole 10m**	**S Pole**	**S Pole 10m**
Power (kWh)					
Power available during day	35,400	59,868	61,185	63,019	65,915
Max power for a month	17,700	50,625	52,876	56,093	61,367
Realistic power for a month	16,461	47,081	49,175	52,167	57,071
Losses	1,239	3,544	3,701	3,927	4,296
Average kWh available	23.25	66.50	69.46	73.68	80.61
Illumination					
Hours of daylight	354	598.68	611.85	630.19	659.15
Hours of night	354	109.32	96.15	77.81	48.85

Table 6.1. Available Power Calculation for Nonpolar, North Pole, and South Pole Sites. Credits: [29].

According to the results obtained, the energy that can be stored in the non-polar regions would be insufficient, so it would be necessary to evaluate only the polar zones for human settlement. To maximize power production and minimize costs, it would be advantageous to focus on the South Pole where the hours of illumination reach up to 659 out of 708 and the power production reaches over 80 kW per hour at 10 meters above soil level (73.68 kW / h on the ground). In total, the available energy would amount to about 63.0 MW at ground level per lunar day.

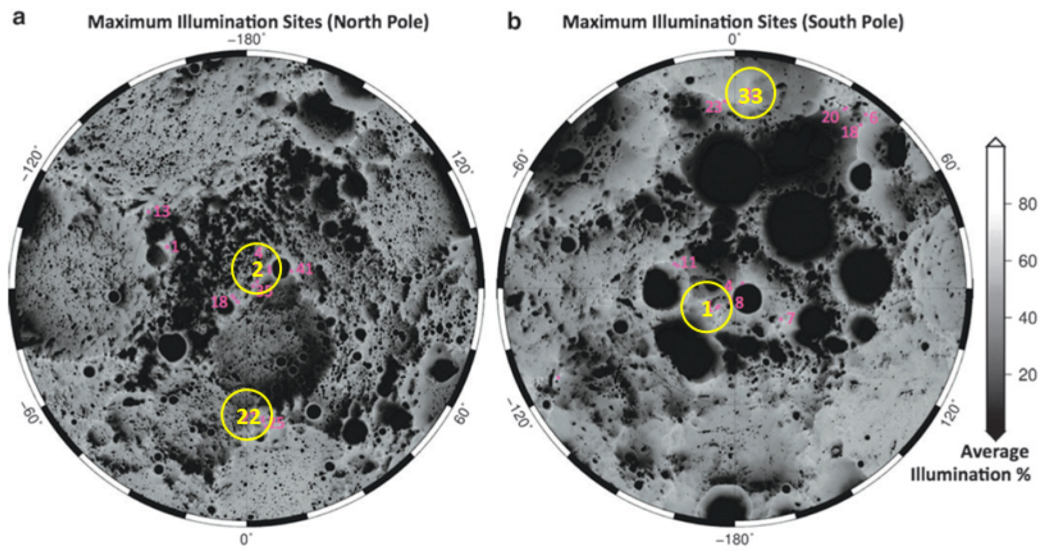

Figure 6.2. Sites of maximum illumination for north (a) and south (b) polar regions. Credits: [29].

6.1.2 Communication

The communications are totally in contrast with what is filtered by the requirements for energy production, in fact any site in non-polar areas would guarantee better communication with the Earth. However, the available power represents a first-level requirements and, therefore, it will be necessary to adapt. At this point it becomes essential to maximize the result with the available resources, going to identify the areas with the best visibility.

A fundamental choice that will have to be made by the architects who will develop the lunar outpost is represented by the type of communication infrastructure: ground-based or space-based. Surely it will involve the use of a lander equipped with a high-bandwidth laser communication system in its development phase, but it is to be evaluated whether this solution allows to contain costs during this phase. The simplest solution would be to use the Lunar Gateway as a relay, a node located in an orbit around a Lagrangian point in the Earth-Moon system. On the other hand, it represents a point of single failure which should be avoided in such a context. A better solution could be to couple a laser relay located on the surface in correspondence of the areas with greater visibility, for example the sites 22 in the North or 33 in the South (Later they will be referred to as 22N and 33S). This would not represent the only advantage brought by this proposal, the use of these relay modules combined with a module installed in the village site, 1S or 2N, would allow to increase the coverage offered to local wireless communications.

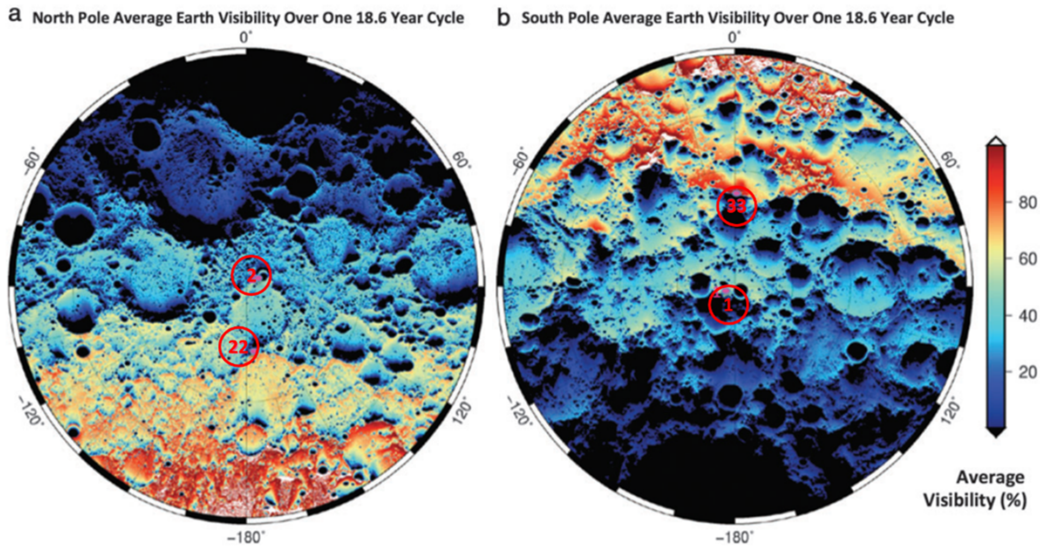

Figure 6.3. Average visibility of the Earth from lunar polar regions: (a) N and (b) S. Credits: [29].

A very important aspect in the evaluation of coverage is the morphology of the territory. Both polar regions have impressive reliefs, and the horizon is only a few kilometers away. The figures below graphically represent the elevation of the soil between sites 2N and 22N, figure a, and between sites 1S and 33S, figure b.

The situation is similar in the two areas, as the difference in elevation between the two sites and the intermediate terrain is important and allows to have very high horizon lines of view, about 113-122 km. The diversity lies in the morphology of the areas between the two sites. The floor of the crater Peary to the north is exceptionally flat with a difference in height of around 200m inside. On the other hand, the land in the South area appears much more jagged and will also complicate the supply of resources.

Considering the ability to be economically viable as a zero-level requirement for the creation of a lunar outpost, the area around the lunar North Pole seems to have the upper hand. However, if adequate communication infrastructure is provided, the Southern area should not be excluded a priori.

6.1.3 Resources

The lunar soil is rich in usable resources. The table below shows the compositions of the soil, in terms of elements, collected from the investigations carried out on the landing sites of the Apollo (A11-A17) and Luna (16-20-24) missions [29]..

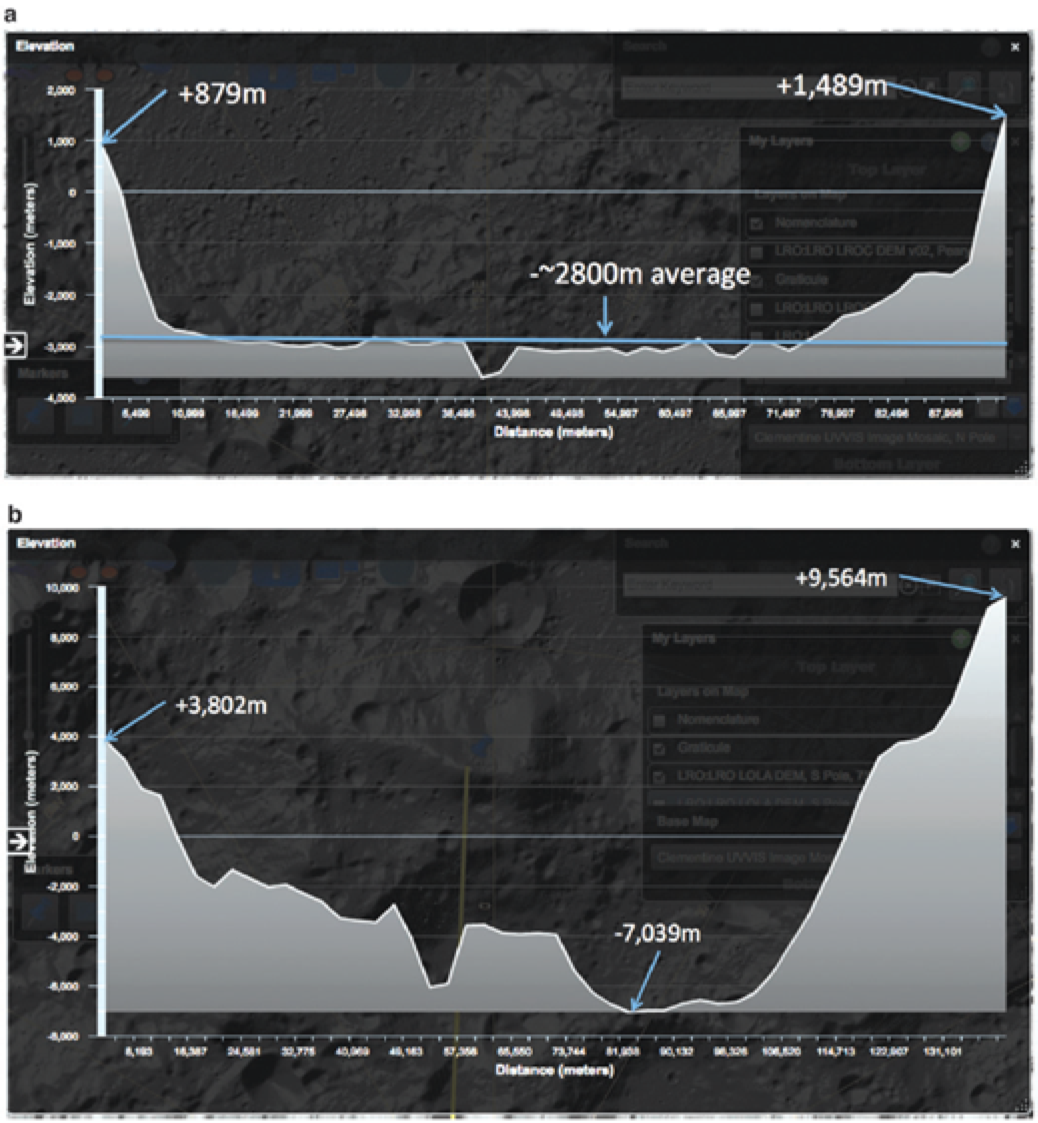

Figure 6.4. Elevation map and distances between 2N and 22N sites, and between 1S and 33S sites. Credits: [29].

The extraction of metals from oxides will not be easy, but the impact of the Moon with some M-class asteroids has also released some free metals and scientists are working to look for new methods that allow them to be used for 3D printing of the building elements of the village. In addition to metals, the presence of water and other volatile elements, or at least hydrogen, will also be needed for the construction of an economically sustainable outpost.

	A11	A12	A15	A16	A17	L16	L20	L24
O, %	41.76	42.29	43.26	44.72	43.61	42.94	44.80	41.73
Na, %	0.35	0.30	0.30	0.35	0.32	0.26	0.29	0.21
Mg, %	4.78	6.28	6.60	3.62	6.00	5.29	5.84	5.95
Al, %	6.66	6.42	7.58	14.41	10.02	8.30	12.04	6.32
Si, %	19.63	21.60	22.06	20.98	20.79	20.74	21.13	21.22
K, %	0.14	0.21	0.13	0.08	0.10	0.09	0.06	0.02
Ca, %	8.39	7.04	7.48	10.41	8.78	8.22	10.51	7.91
Ti, %	4.76	1.56	0.88	0.32	1.70	1.98	0.30	0.62
Fe, %	12.75	13.36	11.64	3.87	8.00	13.02	5.80	15.20
Sm, ppm	13.8	15.1	—	—	7.48	8.29	3.177	1.96
Gd, ppm	18	17	15.6	—	10.1	10.6	4.4	—
Sum, %	99.22	99.07	99.93	98.76	99.33	100.84	100.77	99.19

Table 6.2. Composition of Lunar Landing Sites in Elemental Percentages. Credits: [29].

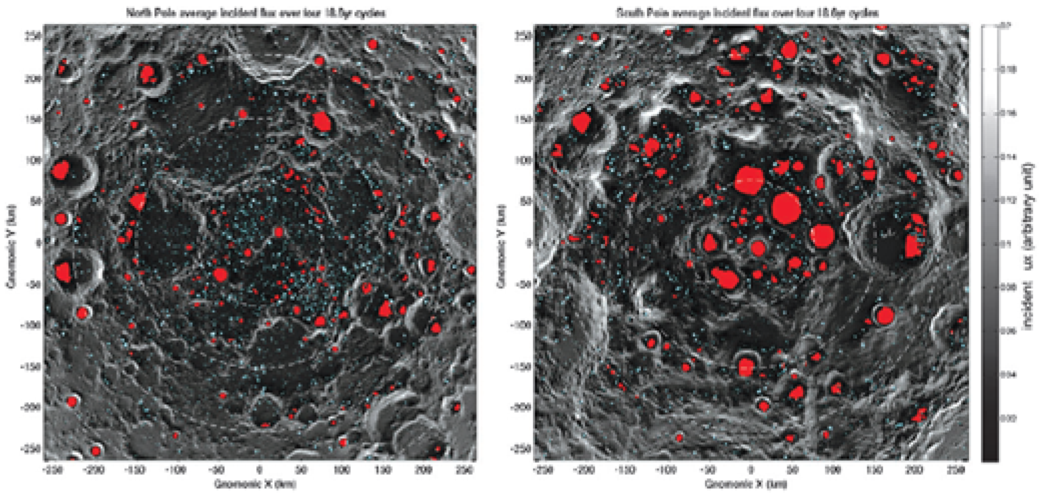

Figure 6.5. Permanently shadowed regions (average over four precession cycles). Credits: [29].

The figure indicates the regions of the South Pole and the North Pole that are perpetually in the shade, an important factor in identifying the possible presence of ice water. From this point of view, the South area is more interesting, as the estimated shaded area reaches over 16,000 km^2, about 20% more than the North area.

To sum up, the polar zones guarantee sufficient lighting for energy production and the southern area has advantages in terms of the presence of resources ready for possible use, while the morphology of the northern area would facilitate communications and the accessibility of resources. To date, the choice made by NASA seems to be regarding an area near the crater Shackleton, at the lunar south pole.

6.2 Defining the path loss model

Once the choice of the possible settlement site has been completed, it becomes essential to evaluate the path losses by relying on pre-existing models or defining new ones. In the literature it is already possible to find several, such as the predictive model that exploits the propagation on an irregular Longley-Rice terrain published by NASA itself, studies that evaluate path losses on the lunar surface considering the diffraction of obstacles, or propagation models for the lunar soil with attached effects on communications. In this chapter the three types mentioned above will be presented.

6.2.1 Modified Longley-Rice irregular terrain model

The use of the modified Longley-Rice model for the prediction of path losses on irregular ground serves to evaluate the difference in signal attenuation between the lunar soil and that which would occur on a reflective sphere [8]. The results provided by this study have been validated by theoretical models and previous analyses for the Apollo missions and seek to provide an assessment of range and coverage limitations for a radio frequency communication link between two nodes on the lunar surface. In addition, the research aims to define a mechanism for path losses to be used for link budget planning and develop margin policies. Among the main influencing factors that modify the previous model used on Earth, we find not only the complex morphology of the territory, but also the composition of the soil itself and the lack of an atmosphere. This translates into the following formula used for the calculation of losses, in which the gains of the two antennas used for the creation of the link and the respective heights at which they are positioned come into play, in addition, of course, to the distance between them.

$$L = \frac{P_{Rx}}{P_{Tx}} = G_{Tx}G_{Rx}(\frac{h_{Tx}h_{Rx}}{d^2})^2 \tag{6.1}$$

The assumption needed to validate this equation is that the distance between the two nodes is much greater than the elevation of the two antennas.

The graph shown in the figure 6.6 shows the differences between the results obtained by evaluating a reflective sphere, an uneven terrain, and the dependence of losses on distance, according to the $\frac{1}{d^4}$ coefficient. The model that considers the

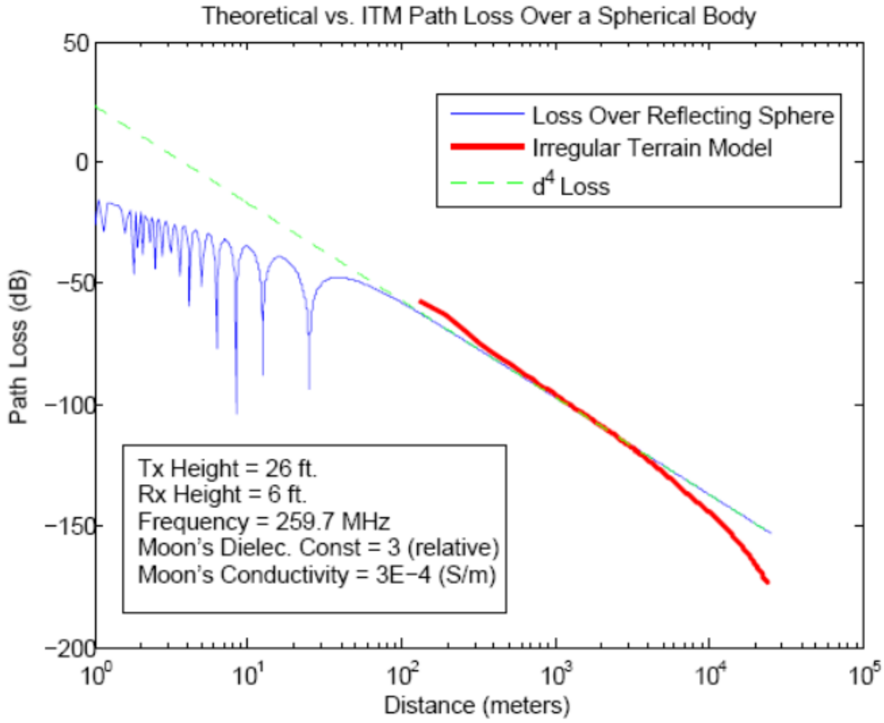

Figure 6.6. Smooth Moon path loss. Credits: [8]

irregularity of the lunar soil reveals slightly better results for distances less than a kilometer and slightly worse than seven kilometers away, as up to one kilometer the destructive interference of reflected rays is reduced due to the amplitude losses of the signal reflected by a highly non-conductive body.

To further improve the analyses, the soil profile should be integrated through elevation data. The results that will be briefly reported below are the result of the following hypotheses:

1. The frequency range investigated ranges between the HF – 30 MHz, UHF – 401 MHz and S – 2.4 GHz bands.
2. The heights of the transmitting antennas follow assumptions about the height of an astronaut (2 m), a rover (3 m), a base station (5 m) and a communication tower (15 m). The receiving antenna always simulates the presence of an explorer (2 m).
3. The average lunar radius is 1,737.4 km.
4. Conductivity and relative dielectric constant are respectively $\sigma = 1 \cdot 10^{-4} S/m$, $\mu_r = 3$.

5. The distance between the transmitter and the receiver located inside a crater is about 1 km.

6. The results are valid for this exploratory study and closely linked to a site with the hypothesized characteristics.

Frequency	**Average fade depth, [dB]**	**Standard deviation [dB]**
Astronaut (height = 2 m)		
30 MHz	N/A	N/A
401 MHz	2.76	2.97
2.4 GHz	6.27	4.65
Rover (height = 3 m)		
30 MHz	1.03	0.61
401 MHz	3.25	3.26
2.4 GHz	6.31	4.98
Base (height = 5 m)		
30 MHz	1.67	1.32
401 MHz	3.70	3.53
2.4 GHz	6.38	5.26
Tower (height = 15 m)		
30 MHz	2.66	2.47
401 MHz	3.35	3.32
2.4 GHz	4.32	5.50

Table 6.3. Summary of results. Credits: [8]

Looking at the results achieved, for a link between astronauts in the HF band the attenuation of the signal is minimal, an aspect that can be explained by the better diffraction capabilities of the selected band. In addition, in many cases the average values obtained are very similar to the standard deviation.

In addition to these attenuation values, corrective parameters will be considered for the evaluation of the link margin, represented by the following equation:

$$M_{Total} = M_{AvgFadeDepth} + M_{CI} \tag{6.2}$$

In which a contribution necessary to achieve the desired confidence interval in coverage is added to the average signal drop. It will correspond to a multiple of the standard deviation value:

1. If added once it will guarantee 68% confidence.

2. If added twice it will guarantee 95% confidence.

3. If added three times it will guarantee 99% confidence.

The margin policies adopted in this study lead to margins of about 15 – 20 dB of excess power, but a factor that has not been considered is the delay of the signal and the possible interference that it can cause.

6.2.2 Lunar Surface with obstacle diffraction model

A study carried out by the Key Laboratory of Radar Imaging and Microwave Photonics (Nanjing, China) proposed to evaluate the propagation of the signal considering the presence of obstacles along the way [24]. For simplicity' use, four cases were presented and compared: a sphere with a smooth surface, one with a rough surface, the presence of a knife-edge obstacle and a rounded one. The decision to simplify the model was dictated by the consideration that most of the radio propagation models are invalid due to the different diffusion in the lunar environment.

To classify the four cases, a parameter is Δh evaluated, index of the reliefs on the surface. If greater than 0.1 times the radius of the first Fresnel zone (F_1)then there is an obstacle, which must then be evaluated depending on its shape as rounded or knife-edge. If lower than this value then the discriminating between the cases of smooth and wrinkled sphere is represented by the ratio with the , when lower is Δh_m considered a smooth sphere, when upper a wrinkled sphere.

Smooth ball

Transmission losses on a smooth sphere can be calculated following three different approaches: the free-space model, the two-ray model and the diffraction loss model. The first is mainly applied for air-to-air or air-to-ground communications, but can be valid in case of lack of obstacles along the way:

$$L_{FreeSpace} = 32.44 + 20 \cdot log(\frac{f}{10^6}) + 20 \cdot log(\frac{d}{10^3}) \tag{6.3}$$

In which f represents the frequency used for transmission and d the distance between the two antennas.

When the distance between the two components increases it becomes necessary to consider the effects of the surface. To do this you can use the two-ray model:

$$L_{Two-Ray} = -10 \cdot log(1 + R_f^2 - 2 \cdot R_f \cdot cos(\Delta\phi)) \tag{6.4}$$

In which $\Delta\phi$ is the phase difference between the line of sight and the reflection path and R_f an equivalent reflection factor that comes into play.

When, on the other hand, the first Fresnel zone is occupied for more than 45% by the lunar surface, the previous method is no longer applicable, and the effects related to diffraction must be added.

$$L_{Diffraction} = [1 - \frac{H_c}{(0.552 \cdot F_1)}] \cdot L_{(D,h)} \tag{6.5}$$

Where H_c indicates the path clearance and $L_{(D,h)}$ diffraction losses on the horizon.

Wrinkled sphere

If a rough sphere is to be considered, the reflection factor$R_f$should be modified considering a spherical diffusion coefficient and an attenuation factor due to the rough surface.

Knife-edge obstacle

This approach allows to evaluate the diffraction of the signal linked to the presence of a sharp obstacle. The attenuation will be a function of a parameter that identifies the normalized path clearance ν, expressed in the form of a function of the distances between the obstacle and the receiving and transmitting antennas.

$$L_{D_{knife-edge}} = -20log(\frac{\sqrt{[1 - cos(\nu) - sin(\nu)]^2 + [cos(\nu) - sin(\nu)]^2}}{2}) \tag{6.6}$$

Where

$$\nu = \theta \cdot \sqrt{2 \cdot \frac{r_{TA} \cdot r_{AR}}{\lambda \cdot r_{TA} + \lambda \cdot r_{AR}}} \tag{6.7}$$

The graphic reproduction shows:

$\theta = \pi - \beta_1 - \beta_2$

With

$$\beta_1 = arccos(\frac{(r_{TA}^2 + (R_0 + h_d)^2 - (R_0 + hT)^2}{2r_{TA}(R_0 + h_d)}) \tag{6.8}$$

$$\beta_2 = arccos(\frac{(r_{AR}^2 + (R_0 + h_d)^2 - (R_0 + hT)^2}{2r_{AR}(R_0 + h_d)}) \tag{6.9}$$

and h_d latitude of the obstacle.

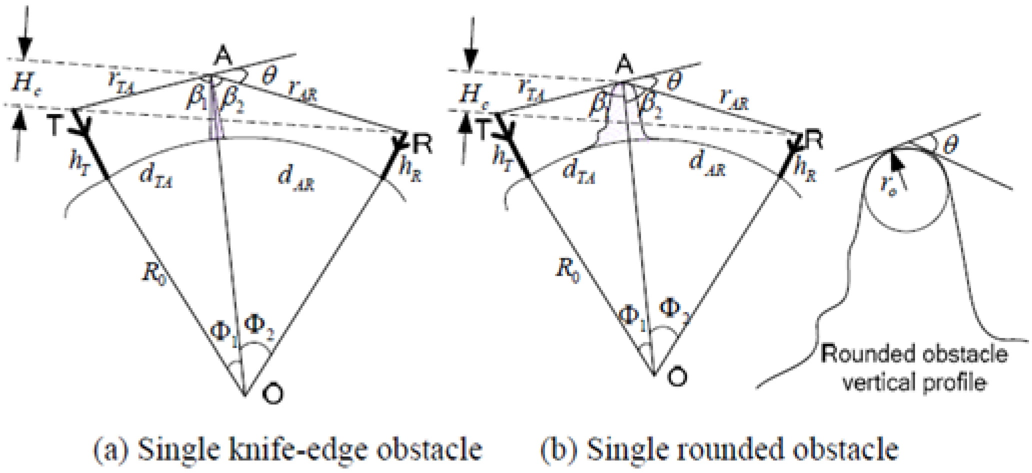

Figure 6.7. Diffraction models of signal knife-edge and signal rounded. Credits: [24].

Rounded obstacle

If the considered obstacle has a rounded shape, it is necessary to add an additional parameter caused by the curvature of the element, then function of two geometric parameters.

$$L_{D_{Rounded}} = L_{D_{knife-edge}} + L_{Curv}(m,n) \tag{6.10}$$

$$L_{Curv}(m,n) = \begin{cases} 7.2m^{\frac{1}{2}} - (2-12.5n)m + 3.6m^{\frac{3}{2}} - 0.8m^2 & mn < 4 \\ -6 - 20log(mn) + 7.2m^{\frac{1}{2}} - (2-17n)m + 3.6m^{\frac{3}{2}} - 0.8m^2 & mn \leq 4 \end{cases}, \tag{6.11}$$

With n, m expressed as:

$$m = r_0 \cdot \frac{\left(\frac{r_{TA}+r_{AR}}{r_{TA}rAR}\right)}{\left(\pi\frac{r_0}{\lambda}\right)^{\frac{1}{3}}}, n = H_c\frac{\left(\pi\frac{r_0}{\lambda}\right)^{\frac{1}{3}}}{r_0} \tag{6.12}$$

The results obtained from these studies show that at the obstacles there is a clear attenuation of the signal and that a pointed obstacle is preferable to one with a rounded surface. For the analyses, a frequency of 259.7 MHz and the values of conductivity and relative dielectric constant of 0.0003 and 3 respectively were used. Transmitter and receiver were placed at 300 meters and obstacles placed at an increasing distance equal to 50, 100 and 150 meters from the transmitter.

An important factor that determined a further analysis was the height of the antennas: the transmitter was made to vary from a height of 7.3 m to one of 5 m, while the receiver followed the reverse path starting from 1. 83 m and rising to 5 m. Below are the results in the presence of a single obstacle.

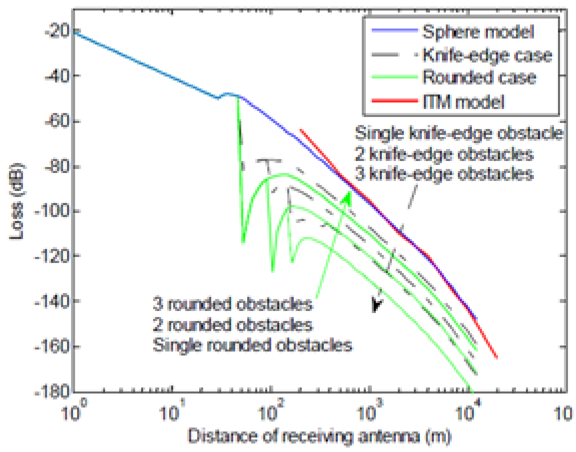

Figure 6.8. Simulation results comparison. Credits: [24].

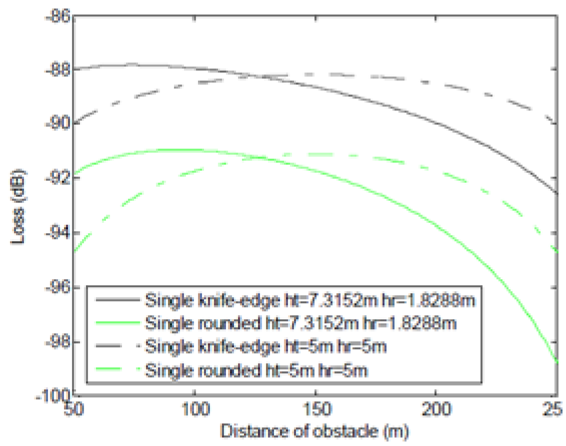

Figure 6.9. Single obstacle loss for difference antenna height Credits: [24].

6.2.3 Effects on lunar wireless communication system

Research conducted by analysts in collaboration with the Johnson Space Center in Houston and presented during the 26th International Communications Satellite Systems Conference (ICSSC) examined signal propagation patterns on the lunar surface to assess the expected effects on NASA's planned wireless communication system [13]. According to the studies carried out, several factors influence the path losses, such as the geometry of the terrain, the positioning of the antennas, the frequency band used and the composition of the lunar soil. In addition, due to phenomena such as diffraction and reflection, the signal often arrives at the receiver from different angles, with different intensities and even presenting a few moments of delay. This aspect implies important possible fluctuations between the attenuation values of the intensity of the received signal.

The method chosen for the evaluation of losses by this study is the Geometrical Theory of Diffraction , capable of considering the phenomena of diffraction and reflection of the lunar soil in three dimensions.

The diffraction and reflection fields at a given point r' are calculated as a function of the incident field at point r, of a diffraction or reflection factor D and of a diffusion factor A evaluated as a function of the distance s between the reflection/diffraction point r and the point of the field of interest r'.

$$E^{r,d}(r') = E^i(r) \cdot D^{r,d} \cdot A^{r,d}(s) \cdot e^{-jks} \tag{6.13}$$

To calculate the total field value, it becomes necessary to consider all contributions:

$$E^{tot} = E^{direct} + \sum_{n=1}^{N} E_n^{reflection} + \sum_{m=1}^{M} E_m^{diffraction} \tag{6.14}$$

The cases examined are mainly two and differ in the morphology of the soil. At first an analysis was carried out linked to a flat surface, while later the propagation inside a crater was evaluated.

Flat Ground Surface

One of the main parameters to have been investigated in this context is the conductivity of the lunar soil. Two types of soil have been envisaged: one with low losses (lossless, Relative Permittivity = 3, Conductivity $=1 \cdot 10^{-1}$ S/m) and one with high losses (lossy, Relative Permittivity = 3, Conductivity $=1 \cdot 10^{-1}$ S/m), in turn compared with free space and the hypothesis of a perfectly electrically conductive soil. The transmission power was normalized to 1 Watt, while signals in two frequencies were evaluated: UHF – 401 MHz and S – 2.1 GHz. Finally, the last parameter that was made to vary is the height of the antennas, with values equal to 2, 6 and 10 meters.

The first fundamental aspect to underline concerns the antenna pattern. Imagining the use of a dipole antenna, the figure shows the differences between the expected pattern and the one resulting considering the effects of the lunar terrain, which, acting as a partial reflective and absorbent of the radio frequency signal, determines a very irregular trend.

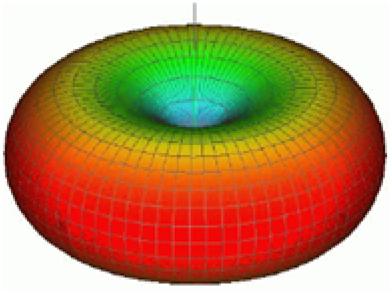

Figure 6.10. The free space dipole antenna pattern. Credits: [13].

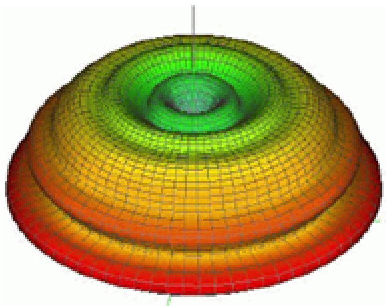

Figure 6.11. The dipole antenna pattern with lunar effect. Credits: [13].

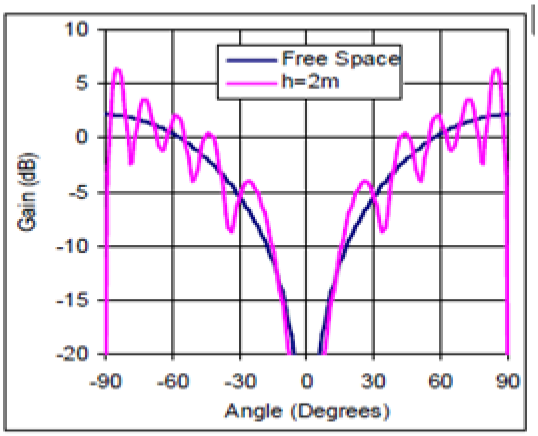

Figure 6.12. The lunar ground effects on a dipole. Credits: [13].

The second aspect to have been investigated is the difference in composition and characteristics of the lunar soil. In this case, using the same frequency, 401 MHz, and placing the transmitter and receiver at the same height, first 6 m and then 2 m, the attenuation of the signal was evaluated as the four types of environments described above varied.

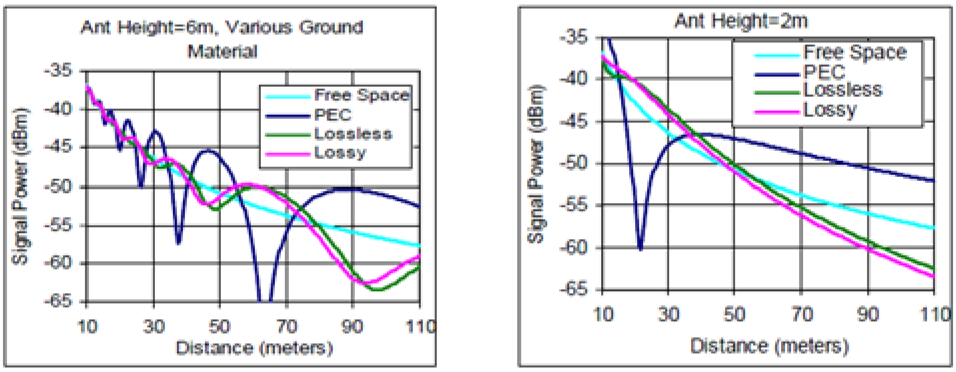

Figure 6.13. The received UHF signal power oscillates with various lunar ground materials at an antenna height of 6 m and 2 m. Credits: [13].

The phenomenon of reflection on the ground causes the oscillations of the signal and it is possible to notice that between a lossy solution and a lossless solution there is only a small phase shift, while a perfectly conductive soil shows very evident negative peaks. As the distance increases, the losses will deviate more and more from the value obtained in the free space and the same trend seems identifiable in the case of vertical approach to the ground, as its effects are greater. To confirm this come the results obtained by studying the effects of the height variation at which the two antennas are positioned.

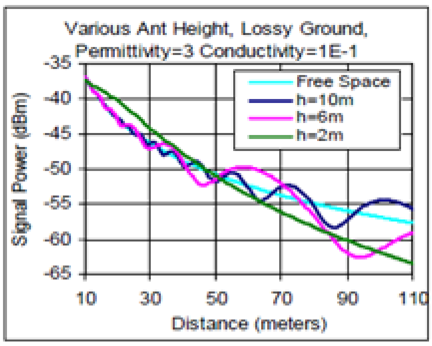

Figure 6.14. The received UHF signal power oscillates due to lunar ground effects with various antenna height. Credits: [13].

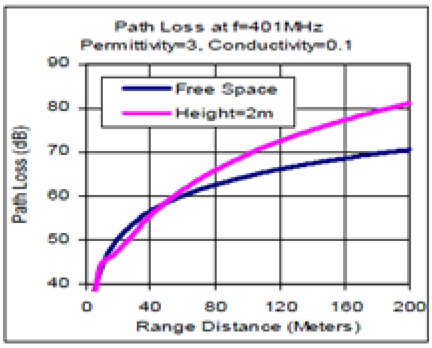

Figure 6.15. The path loss of the UHF signal is greater than free space at range >50 m. Credits: [13].

An antenna farthest from the ground generates minor path losses because it has a greater ground clearance thus approaching the line of sight obtainable by considering to be in the free space. Already at a short distance, about 200 m, the signal transmitted in the UHF band by an antenna placed 2 m above the ground has over 10 dB more attenuation than in a completely free environment. The signal transmitted in the S-band, on the other hand, has an even lower attenuation than in the case of free space, this is because it exploits the constructive interference generated by the waves reflected from the ground. This applies only for short distances; at high ranges the previous situation will recur.

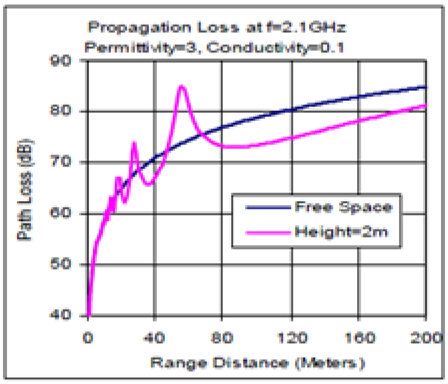

Figure 6.16. The path loss of the S-band signal is less than free space due to the lunar ground effects at 80-200 m. Credits: [13].

The most important result comes from the comparison between the two frequencies used: as the distance between receiver and transmitter increases, the attenuation of the signal stands at similar values, effectively eliminating the dependence of this characteristic on the frequency used.

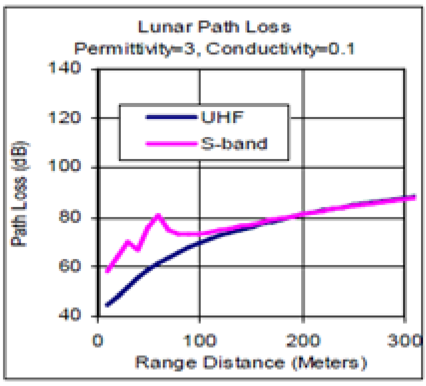

Figure 6.17. The path losses of UHF and S-band signals approach each other at distances great than 180 m. Credits: [13].

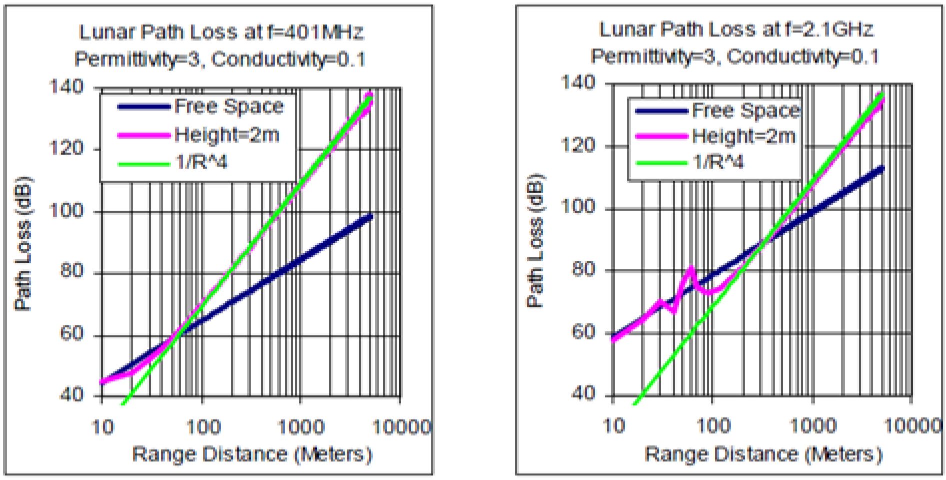

Figure 6.18. The UHF and S-band signal path loss increase in proportion to 1/R2 (blue line) in short range and to 1/R4 (green line) in long range. Credits: [13].

Carrying out a complete analysis of the results catches the eye an important fact. If the communication distance is short, the signal is attenuated as if you were in the free space, although with some oscillations, but following a dependence on the square of the distance traveled. Once a certain breakpoint is passed, for long-range communications the path losses begin to follow a dependence from the high distance to the fourth. The breakpoint will therefore be evaluated and will depend on the frequency used and the elevation of the communication systems with respect to the ground.

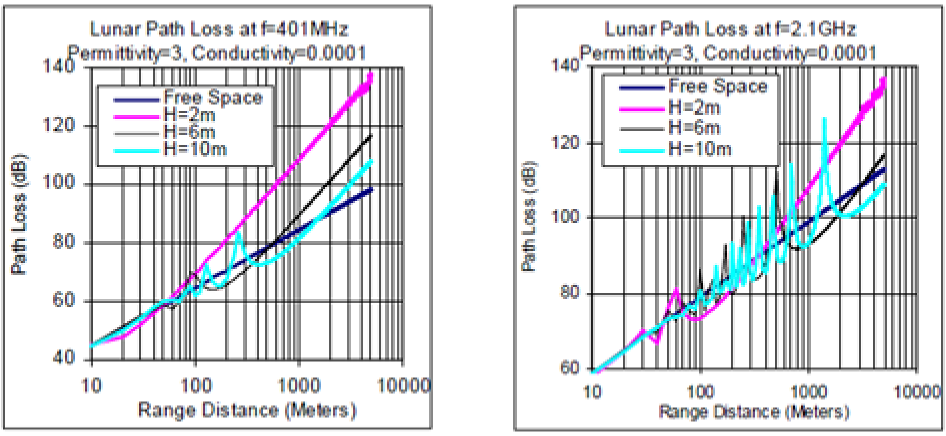

Figure 6.19. The UHF and S-band signal path losses vs. various antenna heights Credits: [13].

As evidenced by the proposed results, increasing the frequency, and moving away from the lunar surface increases the distance that can be traveled before being at the breakpoint.

Lunar crater terrain

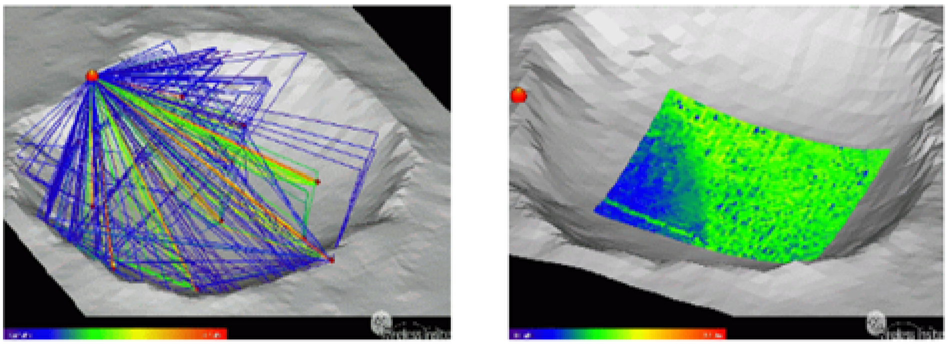

Figure 6.20. Propagation paths and signal strength for receiver points at various locations. Credits: [13].

Since craters are a very common conformation on the lunar soil, an evaluation of the effects that this type of environment generates on communications has been carried out. The main aspects investigated were the strength of the output signal and its delay. The architecture used included a transmitter placed on the edge of the crater and a series of receivers inside, placed at the height of the ground below.

In such an environment, significant reflections, interference, and some shadow areas are also born. The reproductions below show the various paths followed by the output signal and the guaranteed coverage. An important aspect to emphasize is the positioning of the transmitter, the greater its proximity to the edge of the crater, the fewer shadow areas created by the surface.

The diffraction and reflection of the waves generate a difference in power and time of arrival of the signal, sometimes even the polarization is different. For the evaluation of these effects, the signal received at a point on the edge of the crater, exactly in front of the transmitter, was evaluated. The graph shows the direct path followed by the signal and the one followed by the various reflected waves. The results show the presence of a delay in the order of 160 ns.

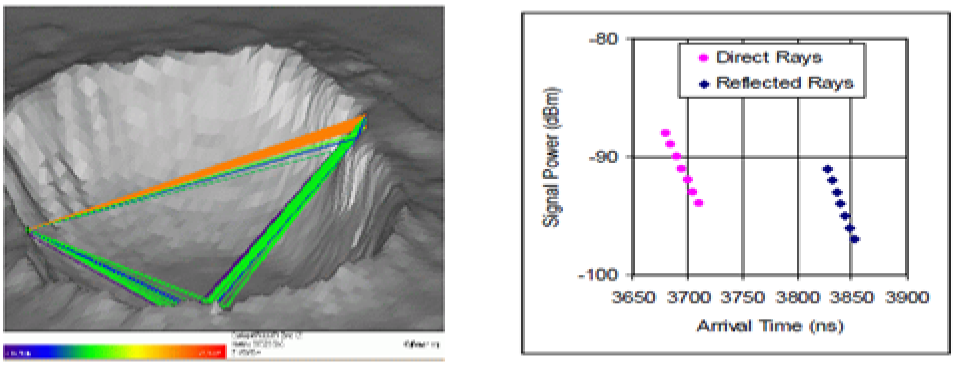

Figure 6.21. The reflected signals. Credits: [13].

To prevent it from becoming a problem for the wireless network and creating inter-symbolic interference, due to bit error, the length of the symbol should not be less than the signal delay.

6.3 Link budget

Note the requirements for the management of communications inside and outside the Moon Village, with high and low data rate links depending on the service to which they are dedicated, it is necessary to couple a series of transmission and reception tools to carry out evaluations and analysis on the budget link. Not a single solution should be considered, but different arrangements, architectures, tools will have to be examined to try to achieve the best possible configuration. All factors previously seen as influencing losses will need to be considered and coupled differently to make these assessments. It will also be essential to choose the instrument that has the most functional characteristics, such as the type of antenna or its gains in transmission and reception.

A first analytical and approximate calculation of the Link Budget can be made using the following formula and evaluating the value obtained for the normalized Signal-to-Noise ratio:

$$\frac{E_b}{N_0} = \frac{P_{Tx} G_{Tx} L_{Tx} G_{Rx}}{k_B T_S R}[Watt] = P_{Tx} + G_{Tx} + L_{Tx} + G_{Rx} - k_B - T_S - R[dB] \quad (6.15)$$

In which the gains of the antenna in reception G_{Rx} and transmission G_{Tx} come into play, the strength of the transmitted signal P_{Tx} and the line losses L_{Tx}(if any) within the transmission system, the Boltzmann constantk_B, the noise temperature reached by the receiving system T_S and the data rate R considered for the link.

6.4 Single cell coverage and network definition

Once the possible values of the $\frac{E_b}{N_0}$ were calculated, losses due to mismatch in the polarization of the signal and those due to the path followed by the wave will be subtracted from it. At this time, it becomes essential to couple the evaluations made previously on the leak model to the link budget obtained to be able to identify the maximum distance at which it is possible to receive the signal on the lunar surface. Each configuration will have a different result and will have to consider a certain margin of safety, which we have seen to be usually a value around 15 – 20 dB, but which can be chosen even higher.

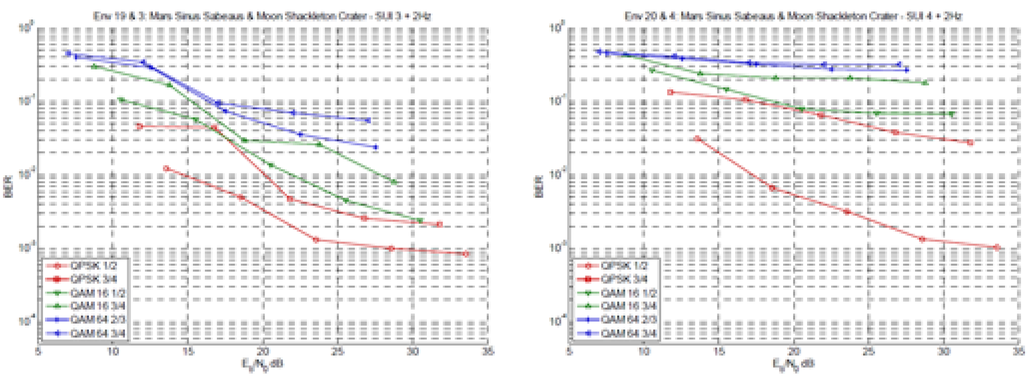

Figure 6.22. $\frac{E_b}{N_0}$ vs Minimun BER at Shackleton crater. Credits: [6].

A feasibility study carried out by deimos space S.r.l, in collaboration with ESA, regarding a reduced system of navigation and planetary communication called

PLANCOM, has evaluated the minimum values required for the operation of communications in some lunar and Martian sites [6].

Taking up the results obtained for a connection between an exploratory vehicle and an astronaut or a Base Station, the $\frac{E_b}{N_0}$ required can be evaluated depending on the modulation used and the minimum Bit Error Rate achievable.

Comparing the value obtained from the studied link with the minimum required, it becomes possible to define the maximum distance for which the two values remain comparable and it is possible to communicate.

At this point we will know the coverage provided by a single cell with certain characteristics and it will be possible to define the network by evaluating the size of each cell. Not all of them will necessarily have the same characteristics, as a different location of the antenna or the presence of obstacles could vary its size.

Once several configurations are ready, several factors can be taken into account for the final choice, including simplicity of construction or an economic evaluation.

Chapter 7

5G lunar surface network simulation

The last chapter of this study aims to present analyses related to the use of the 5G mobile network in lunar communications, recreating some scenarios similar to the expected use cases and coming to provide a preliminary assessment of the maximum size of the communication cells. Once the parameters characterizing the instruments currently in use on Earth by TIM S.p.A. for the distribution of the 5G network have been known, the signal losses due to the lunar environment will be evaluated to define the maximum distance between the receiving system and the transmitter to which it is possible to communicate.

7.1 STK - Systems Tool Kit

Figure 7.1. AGI and STK logo. Credits: AGI.

The achievement of the objective presented above was possible thanks to the use of the Systems Tool Kit software commonly used for digital mission engineering, produced by Analytical Graphics Incorporation (AGI) and distributed in Italy by GMSpazio s.r.l. whom I thank for providing a license contributing to the feasibility of this study. STK is a platform for the visualization and analysis of complex scenarios within a mission, which allows you to interact with data from aerospace, defense, telecommunications, and other industries in the aeronautical sector. These data will then be represented through reports, graphs and 3D animations, completing the simulation of the mission scenario. Its use within this study allowed to simulate the entire mission architecture envisaged for communications, from terminals on planet Earth to those settled in the lunar environment. For the latter, it has guaranteed the possibility of testing the propagation of the signal on the lunar terrain using 5G devices designed to work in the terrestrial environment. The tests were carried out by evaluating the communication links between base stations and 5G user equipment placed at different distances from each other.

7.2 Scenario

Envisaged scenario for the creation of a 5G network on the lunar surface is set in the vicinity of the Shackleton crater, located at the lunar south pole, as per current forecasts of the Artemis program.

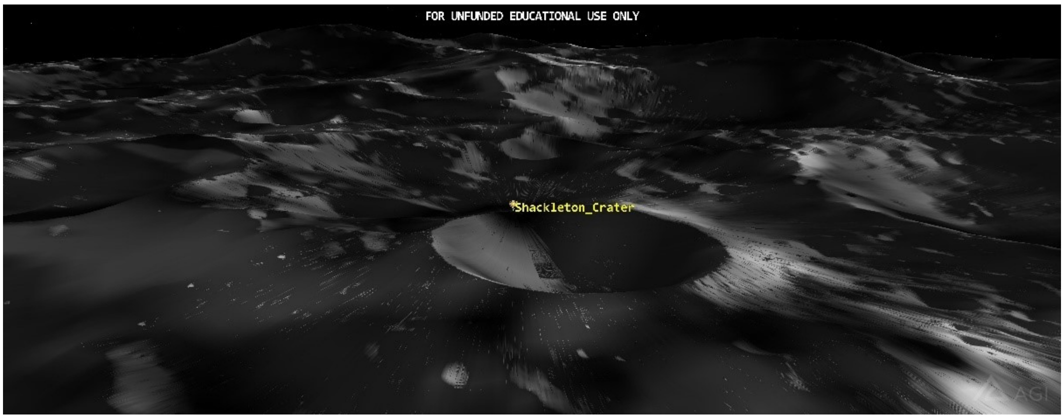

Figure 7.2. Shackleton Crater view. Credits: STK.

The idea is to create a communication network to support a future human settlement. To do this, some elements representing the 5G terminals were placed on the edges of the crater, equipped with transmitters and receivers to evaluate their performances. The terminals were allocated at an increasing distance from the main transmission equipment.

Communication links will be analyzed in two different situations:

1. Link between two Base Stations, to evaluate the coverage area guaranteed by a base station and the maximum distance at which they can be located to be able to transmit data.

2. Link between a Base Station and a User Equipment, to evaluate the maximum distance at which a mobile device can communicate with a fixed station.

Figure 7.3. Terminals location at Shackleton Crater. Credits: STK.

These two cases will cover the scenarios achievable both in case of use of 5G technology for communications within the Moon Village, and for the connections between elements placed in sites of interest.

To complete the scenario, an architecture has been proposed that takes care of the communication link between the lunar village and the mission control centers on Earth. The lack of reliable resources, due to the still embryonic phase of the program and some technologies currently being studied on the ISS, has not allowed to analyze this path from the point of view of the signal.

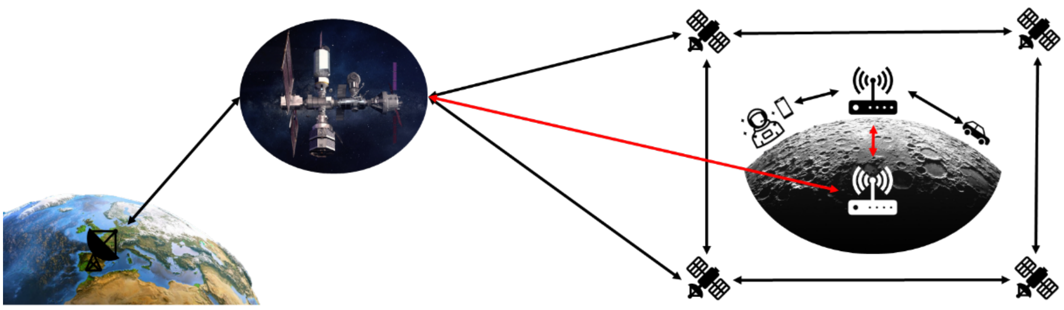

Figure 7.4. Backhaul Link Architecture.

One of the key points for communications with the Earth, and not only, will be the presence of the Lunar Gateway, the outpost orbiting the Moon previously described in chapter 5. It will be represented in the Near Rectilinear Halo Orbit provided for him thanks to the use of the Ephemeris contained in the SPICE file disseminated and available on the Jet Propulsion Laboratory website.

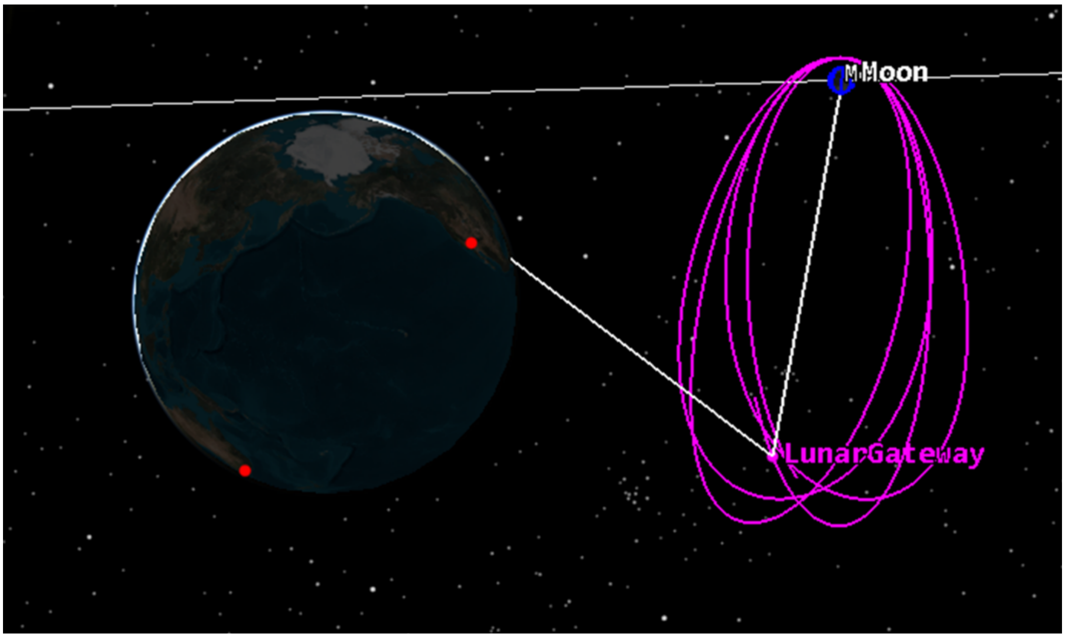

Figure 7.5. Lunar Gateway NRHO orbit. Credits: STK.

Its data will be transmitted directly to the antennas of the Deep Space Network, used by NASA, located in the centers of Tidbinbilla (AUS), Robledo (ESP) and Goldstone (USA).

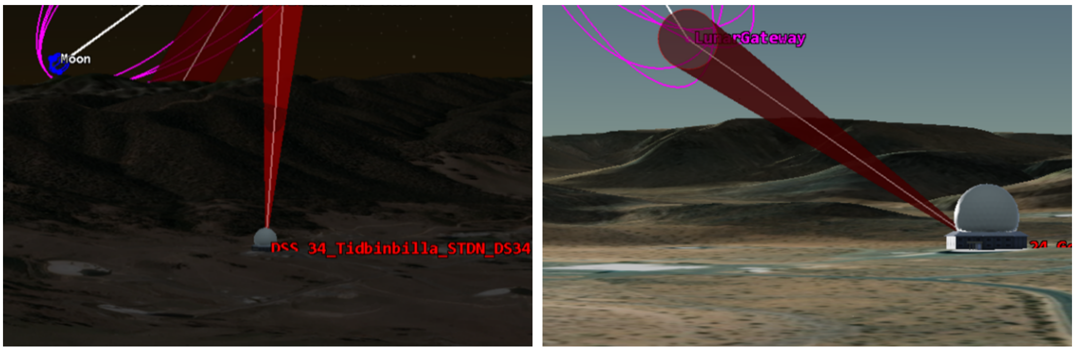

Figure 7.6. DSS 34 at Tidbinbilla, AUS and DSS 24 at Goldstone, USA. Credits: STK.

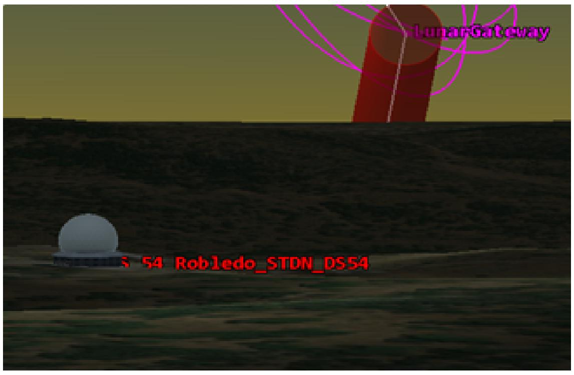

Figure 7.7. DSS 54 at Robledo, ESP. Credits: STK.

Station	Latitude	Longitude	Height [m]
DSS 24	35°20'23.61555"	243°7'30.74842"	0952.156
DSS 34	-35°23'54.53995"	148°58'55.06320"	0692.750
DSS 54	40°25'27.75526"	355°44'48.99940"	0823.939

Table 7.1. DSS 24, 34 and 54 Coordinates.

Communications will take place in -X, -S or Ka bands, bands currently supported and in use for communications with lunar spacecraft. Below is the access data between the Lunar Gateway and the constellation of antennas of the DSN, highlighting the periods when access will not be available since the two objects are not in line of sight.

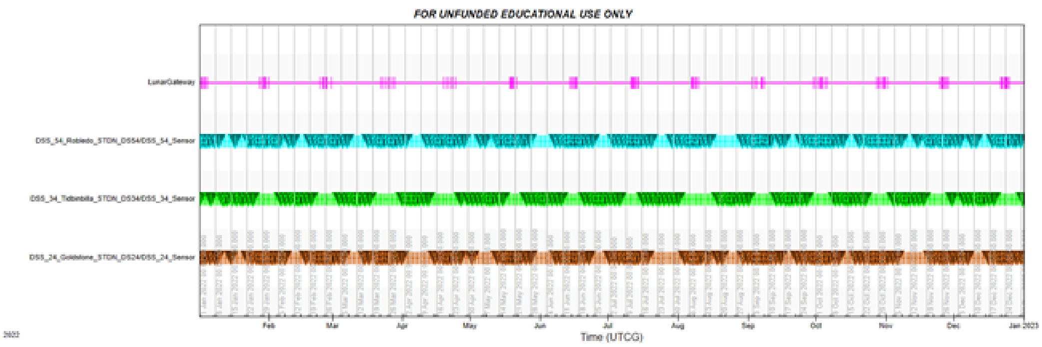

Figure 7.8. Access between DSN stations and Lunar Gateway during 2022. Credits: STK.

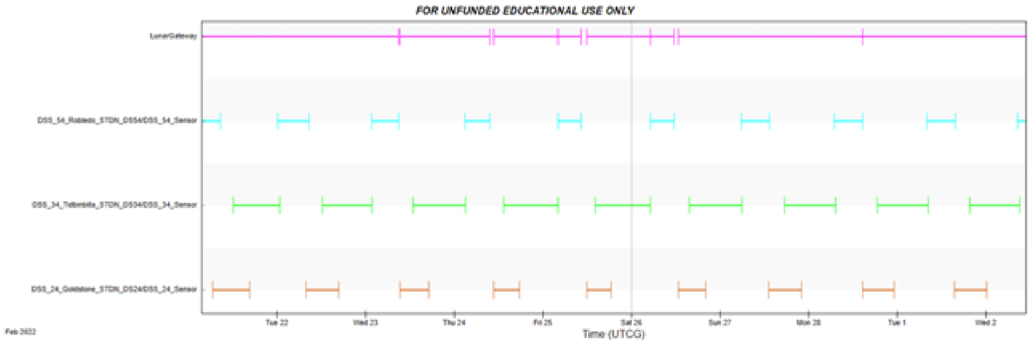

Figure 7.9. Access between DSN stations and Lunar Gateway, February 22nd 2022 - March 2nd 2022. Credits: STK.

For the connection between the lunar village and the lunar Gateway, now there are two options under consideration. The first involves the use of a constellation of satellites orbiting the moon that receives the signal leaving the village and transmits it back to the Lunar Gateway. This solution seems difficult to implement due to the use of resources necessary for the putting into orbit of such a quantity of satellites, although it would benefit communications by making link always available, even during the passages of the gateway above the lunar North Pole. The second solution would involve the use of a laser terminal for the transmission of the signal from the village to the Gateway and would be located a few kilometers away from the village, in an area more favorable to communications due to the conformation of the terrain. Its strength is represented by the simplicity of construction and the possibility of having a redundancy terminal that can be used to communicate directly with the gateway. On the other hand, laser technology for communications is still being developed and tested on board the ISS, so now, we are not sure if it is a viable path. The best solution would probably be a mix of the previous ones, that uses a laser terminal located in a smoother area of the Shackleton crater for communications and that presents a reduced number of orbiting satellites to ensure an always available connection.

7.3 5G terminal characterization

To carry out the analysis of the communication links between 5G terminals they were reproduced by inserting a transmitter and a receiver attached to an element representing the device. The data used for their characterization correspond to the parameters with which the terminals disseminated by Tim S.p.A. are currently configured, and, therefore, we thank the company again for having provided them.

7.3.1 5G Base Station

BASE STATION 5G				
Frequency	3.5 - 3.7	GHz		
Transmitting Power	280	W		
Antenna Gain	18.6 25.5	dBi dBi	Broadcast Traffic Envelope	
EIRP	73 77	dBm dBm	Broadcast Traffic Envelope	
Beamwidth	6 65 6 100	deg deg deg deg	Broadcast Broadcast Traffic Envelope Traffic Envelope	Vertical Horizontal Vertical Horizontal
Polarization	45 -45	deg deg		
Modulation	5G NR	OFDM		
Bandwidth	200	MHz		
LNA Noise Figure	5.9	dB		

Table 7.2. TIM S.p.A. 5G Base Station characteristics. Credits: TIM S.p.A.

The Base Stations were reproduced using the parameters above.

The data provided highlight the possibility of transmitting in two modes: Broadcast and Traffic Envelope. The values set reflect the broadcast mode, as they represent the most restrictive parameters. In transmission, a complex model of transmitter was used, useful for defining the output signal strength and the desired data rate. The antenna was modeled with a rectangular pattern that reproduced the directional beam characteristic of 5G technology. A QPSK modulation of the signal has been envisaged, as the 5G mobile network respect the 5G NR standard and uses an OFDM modulation, a multi-carrier in which each carrier uses a basic modulation technique. The choice fell on the QPSK modulation since it is indicated as the one used for transmissions between user equipment. For this kind of modulation in the Shackleton crater scenario the minimum Eb/N0 required is 35 dB, considering the worst case, as previously presented in chapter 6.

In reception it was assumed to have an antenna with the same characteristics. About the noise temperature of the receiving system, the components related to the losses between antenna, LNA and receiver were considered negligible as they are all inside the same component. For the evaluation of this parameter, therefore, only the noise figure of the receiver and the noise temperature of the antenna, set at a standard value of 290 K, came into play.

7.3.2 5G User Equipment

USER EQUIPMENT 5G			
Frequency	3.75	GHz	
Transmitting Power	22.5 19.6	dBm dBm	CPE SMARTPHONE
Antenna Gain	5.5 6.4	dBm dBm	CPE SMARTPHONE
EIRP	28 26	dBm dBm	CPE SMARTPHONE
Modulation	QPSK		

Table 7.3. TIM S.p.A. 5G User Equipment characteristics. Credits: TIM S.p.A.

As anticipated in chapter 5, the idea proposed by Nokia is to equip astronauts, rovers and other moving elements with user equipment currently in use on smartphones or other mobile terminals. For this simulation Tim S.p.A. has provided some parameters characterizing mobile devices, dividing them according to whether they are Customer Premise Equipment (CPE) or Smartphones. Between the two options it was chosen to use the values related to a smartphone as they are more stringent. This time the transmitter and the receiver have been characterized with simple models, however able to reproduce the characteristics of the antenna used but defined through the Effective Isotropic Radiative Power (EIRP) in transmission and the ratio between gain and system noise temperature (G / T) in reception. The modulation technique used for signal transmission is QPSK.

7.4 Test link between 5G Base Stations

As anticipated, the first series of tests was useful to study a communication link between two base stations located on the edge of the crater Shackleton.

In the architecture examined there is a Central Base Station equipped with a transmitter for sending the signal and a series of secondary Base Stations equipped with a receiver. Their positioning has always taken place on the edge of the crater

Figure 7.10. 5G Base Station locations around Shackleton Crater. Credits: STK.

and at an increasing distance from the source of emission of the signal, in particular distances of about 100, 500, 1000 and 2000 meters have been considered. This type of analysis is useful to evaluate the increase in signal propagation losses due to the increase in the distance traveled. In addition, for each Base Station an evaluation was carried out at two different heights above the ground, imagining two different scenarios that present an antenna placed 5 meters from the ground or 10 meters above the ground. These two situations are realistic as they aim to recreate the positioning of the device above a descent module, a housing module, or some small communication towers.

LUNAR SITE	Shackleton Crater			
	Coordinate		Distance from Base Station 1 [m]	Terrain height [m]
	Latitude[°]	Longitude [°]		
5G Base Station 1 TX	-89.9500	50.0000	0	1257.8
5G Base Station 2 RX	-89.9535	50.0000	106	1246.2
5G Base Station 3 RX	-89.9670	50.0000	516	1243.2
5G Base Station 4 RX	-89.9160	50.0000	1032	1287.7
5G Base Station 5 RX	-89.8830	50.0000	2034	1317.7

Table 7.4. 5G Base Station coordinates.

Given the directivity and directionality of the signal guaranteed by an active antenna that uses 5G technology, the accesses have been calculated always considering the main emission lobe in direct vision of the main lobe in reception to maximize the strength of the received signal.

Data Rate	
10	Gbit/s
1	Gbit/s
100	Mbit/s
10	Mbit/s

Table 7.5. Used Data rates.

As introduced in chapter 4, the usage scenarios and communication services to be offered could be multiple, for this reason the analysis has considered a variable data rate between a more reliable and low-speed connection, 10 Mbit/s, and a faster pier but that has a greater impact on the link budget, 10 Gbit/s.

Once the elements and parameters have been defined and the variables have been selected, we have moved on to the evaluation of the budget link. At first, only signal losses due to the space traveled by the wave (Free Space) were considered, without taking in count the morphology of the underlying terrain. The use of this loss model, although unrealistic, was useful to get an idea of the ranges of variation of the most important variables, such as the distance between the two base stations and the data rate used.

Data Rate [Gbit/s]	BS height above Ground [m]	Distance from Base Station 1 [m]	Path Loss Model	Free Space Losses [dB]	Received Isotropic Power [dBW]	BER	Eb/N0 [dB]
10	5	106	Free Space	83.9034	-40.832	1.00E-30	75.843
10	5	516	Free Space	97.5834	-54.512	1.00E-30	62.163
10	5	1032	Free Space	103.6043	-60.533	1.00E-30	56.142
10	5	2034	Free Space	109.4964	-66.425	1.00E-30	50.250

Table 7.6. Base Station to Base Station link results with only free space losses.

At this point it is necessary to also consider all the components of loss due to the presence of an irregular terrain. To do this, the most suitable tool is represented by the TIREM module integrated in STK. TIREM stands for Terrain Integrated Rough Earth Model and represents an extension of the application that allows to consider the propagation of the radio frequency signal on an irregular terrain, on the sea surface and evaluating the effects due to the connection beyond the line of sight, to the phenomena of reflection and diffraction of the waves. Unfortunately, currently this module is exploitable only on the Earth's surface, so referring to the process used by previous studies [13], it was chosen to evaluate the amount of losses due to the lunar soil considering a site with similar characteristics present on Earth. The choice fell on the crater Meteor located in Arizona, USA.

Figure 7.11. Meteor crater terrain. Credits: STK.

Once a range of values for this type of losses has been collected, these will be incorporated into the data obtained considering only the free space losses in the lunar scenario. The simulations were carried out by setting the reference parameters of the TIREM module as if the terrain belonged to the Moon. Therefore, the analyzes were carried out with a temperature varying between -100 ° C and + 100 ° C, limit values accepted by the software to simulate conditions of full illumination or full shadow of the surface. In addition, as suggested by the same study [13], a soil with variable surface conductivity was considered to study its effects. Below are the features used and relative results.

EARTH SITE	Meteor Crater			
	Coordinate		Distance from Base Station 1 [m]	Terrain height [m]
	Latitude[°]	Longitude [°]		
5G Base Station 1 TX	35.0225	-111.0220	0	1728.1
5G Base Station 2 RX	35.0223	-111.0230	100	1736.7
5G Base Station 3 RX	35.0218	-111.0250	513	1733.5

Table 7.7. 5G Base Station coordinates at Meteor crater, Arizona, USA.

	Lossy Terrain	Lossless Terrain
Relative Permittivity	3	3
Surface conductivity[S/m]	$1 \cdot 10^{-1}$	$1 \cdot 10^{-5}$

Table 7.8. Terrain properties.

Data Rate [Gbit/s]	Terrain Type	Surface Temperature [°C]	BS height above Ground [m]	Distance from Base Station 1 [m]	Path Loss Model	TIREM losses along Meteor crater [dB]
10	Lossy	100	5	100	TIREM	18.8119
10	Lossy	100	5	513	TIREM	21.4425
10	Lossy	100	10	100	TIREM	0
10	Lossy	100	10	513	TIREM	0
10	Lossless	100	5	100	TIREM	18.8119
10	Lossless	100	5	513	TIREM	21.4425
10	Lossless	100	10	100	TIREM	0
10	Lossless	100	10	513	TIREM	0
10	Lossy	-100	5	100	TIREM	18.8119
10	Lossy	-100	5	513	TIREM	21.4425
10	Lossy	-100	10	100	TIREM	0
10	Lossy	-100	10	513	TIREM	0
10	Lossless	-100	5	100	TIREM	18.8119
10	Lossless	-100	5	513	TIREM	21.4425
10	Lossless	-100	10	100	TIREM	0
10	Lossless	-100	10	513	TIREM	0

Table 7.9. Base Station to Base Station link results considering terrain effect.

Once the final budget link was obtained from the integration of the data obtained, a link margin of 20 dB was added, as suggested [8], going to consider the greater value for greater reliability. Below are the results obtained for a link between two Base Stations.

7.5 Test link between 5G Base Sation and user Equipment

The second scenario to have been analyzed presents a communication link between a mobile device and a base station, in particular the transmission of a signal by the user equipment and its reception by the Base Station was evaluated. Again, all the elements are located on the edge of the crater Shackleton.

In this case the distances considered between the user equipment and the base

Data Rate [Gbit/s]	BS height above Ground [m]	Distance from Base Station 1 [m]	Eb/N0	Link margin	Eb/N0	TIREM losses along Meteor crater [dB]	Eb/N0
10	5	100	75.843	20	55.843	18.8119	37.031
10	5	513	62.163	20	42.163	21.4425	20.720
10	10	100	75.843	20	55.843	0	55.843
10	10	513	62.163	20	42.163	0	42.163
1	5	100	85.840	20	65.843	18.8119	47.031
1	5	513	72.163	20	52.163	21.4425	30.720
1	10	100	85.843	20	65.843	0	65.843
1	10	513	72.163	20	52.163	0	52.163
0.1	5	100	95.843	20	75.843	18.8119	57.031
0.1	5	513	82.163	20	62.163	21.4425	40.720
0.1	10	100	95.843	20	75.843	0	75.843
0.1	10	513	82.163	20	62.163	0	62.163
0.01	5	100	105.84	20	85.843	18.8119	67.031
0.01	5	513	92.163	20	72.163	21.4425	50.720
0.01	10	100	105.84	20	85.843	0	85.843
0.01	10	513	92.163	20	72.163	0	72.163

Table 7.10. Base Station to Base Station link results.

LUNAR SITE	Shackleton Crater			
	Coordinate		Distance from Base Station 1 [m]	Terrain height [m]
	Latitude[°]	Longitude [°]		
5G Base Station 1 RX	-89.9500	50.0000	0	1257.8
5G User equipment 2 TX	-89.9535	50.0000	106	1246.2
5G User equipment 3 TX	-89.9670	50.0000	516	1243.2
5G User equipment 4 TX	-89.9160	50.0000	1032	1287.7
5G User equipment 5 TX	-89.8830	50.0000	2034	1317.7

Table 7.11. 5G User equipments coordinates.

station do not exceed 500 m, since beyond the communication it is no longer possible. For both elements, different heights with respect to the ground were evaluated. The base station varies its position between 5 and 10 meters on the ground as in the previous case, the user equipment varies its height between 2 and 3 meters to simulate the presence of an astronaut or a lunar rover.

The range of data rates studied was kept the same as in the previous case.

Following the same procedure used for the analysis of communications between base stations, the link budgets were evaluated, considering only the losses for free space at first and then adding the contribution related to the soil provided using the TIREM module.

At this point a link margin of 20 dB was considered again, which allowed to obtain the results.

Data Rate [Gbit/s]	BS height above Ground Rx[m]	UE height above Ground Tx [m]	Dist. from BS 1 [m]	Path Loss Model	Free Space Losses [dB]	Received Isotropic Power [dBW]	BER	Eb/N0 [dB]
10	5	2	106	Free Space	84.5323	-88.532	1.00E-30	28.142
10	5	3	106	Free Space	84.5217	-88.522	1.00E-30	28.153
10	10	2	106	Free Space	84.5963	-88.596	1.00E-30	28.078
10	10	3	106	Free Space	84.5821	-88.582	1.00E-30	28.093
10	5	2	516	Free Space	98.1842	-102.184	3.19E-14	14.490
10	5	3	516	Free Space	98.1837	-102.184	3.18E-14	14.491
10	10	2	516	Free Space	98.1875	-102.188	3.26E-14	14.487
10	10	3	516	Free Space	98.1868	-102.187	3.25E-14	14.488

Table 7.12. User equipment to Base Station link results with only free space losses.

EARTH SITE	Meteor Crater			
	Coordinate		Distance from Base Station 1 [m]	Terrain height [m]
	Latitude[°]	Longitude [°]		
5G Base Station 1 RX	35.0225	-111.0220	0	1728.1
5G User Equipment 1 RX	35.0223	-111.0230	100	1736.7
5G User Equipment 2 RX	35.0218	-111.0250	513	1733.5

Table 7.13. 5G User Equipment coordinates at Meteor crater, Arizona, USA.

Data Rate [Gbit/s]	Terrain Type	BS height above Ground RX [m]	UE height above Ground TX [m]	Distance from Base Station 1 [m]	Path Loss Model	TIREM losses along Meteor crater [dB]
10	Lossless	5	2	100	TIREM	23.2355
10	Lossless	5	3	100	TIREM	22.0462
10	Lossless	10	2	100	TIREM	10.1068
10	Lossless	10	3	100	TIREM	6.4447
10	Lossless	5	2	513	TIREM	28.3173
10	Lossless	5	3	513	TIREM	22.9711
10	Lossless	10	2	513	TIREM	27.2114
10	Lossless	10	3	513	TIREM	21.6777

Table 7.14. User Equipment to Base Station link results considering terrain effect.

Data Rate [Gbit/s]	BS height above Ground RX [m]	UE height above Ground TX [m]	Dist. from BS 1 [m]	Eb/N0	Link margin	Eb/N0	TIREM losses along Meteor crater [dB]	Eb/N0
10	5	2	100	28.1428	20	8.1428	23.2355	-15.0927
10	5	3	100	28.1534	20	8.1534	22.0462	-13.8928
10	10	2	100	28.0788	20	8.0788	10.1068	-2.028
10	10	3	100	28.0931	20	8.0931	6.4447	1.6484
10	5	2	513	14.4909	20	-5.5091	28.3173	-33.8264
10	5	3	513	14.4915	20	-5.5085	22.9711	-28.4796
10	10	2	513	14.4876	20	-5.5124	27.2114	-32.7238
10	10	3	513	14.4884	20	-5.5116	21.6777	-27.1893
1	5	2	100	38.1428	20	18.1428	23.2355	-5.0927
1	5	3	100	38.1534	20	18.1534	22.0462	-3.8928
1	10	2	100	38.0788	20	18.0788	10.1068	7.972
1	10	3	100	38.0931	20	18.0931	6.4447	11.6484
1	5	2	513	24.4909	20	4.4909	28.3173	-23.8264
1	5	3	513	24.4915	20	4.4915	22.9711	-18.4796
1	10	2	513	24.4876	20	4.4876	27.2114	-22.7238
1	10	3	513	24.4884	20	4.4884	21.6777	-17.1893
0.1	5	2	100	48.1428	20	28.1428	23.2355	4.9073
0.1	5	3	100	48.1534	20	28.1534	22.0462	6.1072
0.1	10	2	100	48.0788	20	28.0788	10.1068	17.972
0.1	10	3	100	48.0931	20	28.0931	6.4447	21.6484
0.1	5	2	513	34.4909	20	14.4909	28.3173	-13.8264
0.1	5	3	513	34.4915	20	14.4915	22.9711	-8.4796
0.1	10	2	513	34.4876	20	14.4876	27.2114	-12.7238
0.1	10	3	513	34.4884	20	14.4884	21.6777	-7.1893
0.01	5	2	100	58.1428	20	38.1428	23.2355	14.9073
0.01	5	3	100	58.1534	20	38.1534	22.0462	16.1072
0.01	10	2	100	58.0788	20	38.0788	10.1068	27.972
0.01	10	3	100	58.0931	20	38.0931	6.4447	31.6484
0.01	5	2	513	44.4909	20	24.4909	28.3173	-3.8264
0.01	5	3	513	44.4915	20	24.4915	22.9711	1.5204
0.01	10	2	513	44.4876	20	24.4876	27.2114	-2.7238
0.01	10	3	513	44.4884	20	24.4884	21.6777	2.8107

Table 7.15. User Equipment to Base Station link results.

Chapter 8

Discussion and conclusions

Within this thesis, the main needs regarding communications for the future of space exploration and how the characteristics of the 5G mobile network can be exploited satisfying these requirements were presented. The focal point of the simulations carried out was to evaluate the 5G devices currently in use on Earth, without changing their structure. This aspect was mainly linked to the fact that it was a preliminary study, with the idea of following a policy of containing costs and complexity of the network infrastructure design process. The use of STK software made it possible to carry out the analyzes presented, but the impossibility of evaluating the effect of the lunar soil led to the consideration of the effects on a representative terrestrial soil, placing on the results an uncertainty linked to the hypothesis carried out.

The first scenario analyzed, a communication link between two 5G Base Stations, confirmed some expected results and allowed to restrict the number of cases for subsequent evaluations. The study of the connection considering only the losses due to the distance traveled by the signal has confirmed that this parameter depends only on the actual distance between the two communicating stations, without their height above the ground influencing the trend. The greater the distance, the lower the Eb/N0 ratio. The results obtained with the use of the TIREM module for the evaluation of the effects related to the presence of an irregular terrain have shown that the variation in environmental temperature does not produce significant effects on communications, nevertheless the direct transition from the shadow area to an area exposed to sunlight involves substantial differences from the point of view of the power supply of the devices themselves and as regards the radiation absorbed by the component. Unlike the results presented by previous study [13], the different composition of the lunar soil, in particular its surface conductivity, does not produce considerable variations of Eb/N0. However, this could be due to a limitation of the ranges of values that can be set in the instrument used, as the low conductivity soil was represented with a value equal to

$1 \cdot 10^{-5}$ S / m against the $1 \cdot 10^{-11}$ S / m used by the aforementioned paper. The increase in the elevation of the Base Stations above the ground has instead met expectations, allowing to have a lower impact of the ground and respectively less losses. At 10 meters from the surface the considerable contribution is practically nil. Compared to an urban terrestrial environment, the lack of vegetation and buildings helps to reduce the impact of these losses. An important note is that the influence of the terrain is not linked to the distance between the two Base Stations by a precise relationship, but the increase in space traveled by the wave obviously affects the probability that there is an obstacle or some irregularities of the terrain. The results obtained at this point and reported in Table 7.10 allow to restrict the evaluation field to the stations within 500 meters from the signal source, as the study [6] presented in chapter 6 indicates that in the surroundings of the Shackleton a minimum value of Eb/ N0 equal to 30/35 dB is required for the selected modulation. This consideration is useful if you want to evaluate a transmission that travels at the highest possible speed, 10 Gbit/s, as reducing it would be possible to increase by 10 dB the value of Eb/N0 for each order of magnitude less in terms of data rate. By analyzing the results, it is therefore possible to guarantee a communication link under the previously exposed conditions, with a data rate of 10 Gbit/s, up to about 500 meters away by placing the antennas of the Base Stations at a height of 10 meters. Placing them 5 meters above the ground, to maintain the same range it is necessary to decrease the data rate used up to a few hundred Megabits per second.

The second scenario analyzed provided for the study of a communication link between a transmitting User Equipment and a receiving Base Station, an architecture chosen as it was considered more binding than the opposite. The first evaluation containing only the path losses allowed to find the same effects described for the previous case, but the maximum simulated distance between the two devices is equal to about 500 meters when the signal to noise ratio values were already critical. The use of the TIREM module to consider the effect of the terrain followed, also in this case, the trend of the first scenario. The substantial difference occurred in the variation of losses by placing the Base Station at a height of 10 meters, as the transmitting device was located a few meters above the ground, and this resulted in a non-negligible contribution. Looking at the values obtained after considering the effect of the lunar soil and a link margin equal to 20 dB, it can be seen that many values of Eb/N0 are negative, therefore not acceptable. The few acceptable cases are concentrated at a maximum distance between the two elements equal to 100 meters, which must be associated with the use of a low data rate, around 10 Mbit/s, as shown in Table 7.15. The results provided are however encouraging and with the introduction of some small technological improvement or a more powerful mobile device they will be easily improved.

Summarizing the evaluations carried out for the two scenarios, the maximum distance to which two Base Stations could communicate is about 500 meters, while a User Equipment would be able to connect only being about 100 meters.

At this point the conceivable architecture could provide cells with a radius of 100 meters in the village area, where the Base Stations located 200 meters away from each other could transmit data without problems. Unlike what happens on Earth, it is currently not conceivable to connect them by cable, as it would involve a considerable economic outlay and design effort for the transfer and installation of materials.

Below are two communication chains that have been tested:

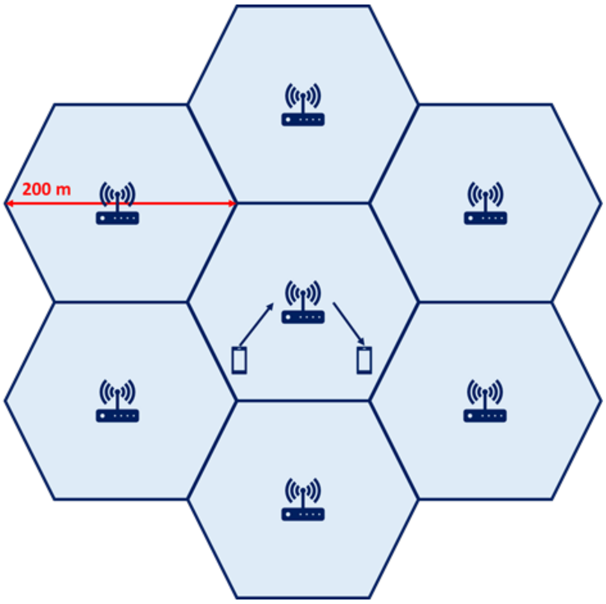

Figure 8.1. Possible link between two User Equipments inside the same 5G lunar network cell. - Short range communications.

LUNAR SITE	Shackleton Crater			
	Coordinate		Distance from Base Station 1 [m]	Terrain height [m]
	Latitude[°]	Longitude [°]		
5G Base Station 1 RX	-89.9500	50.0000	0	1257.7
5G User Equipment 1 TX	-89.9535	50.0000	108	1246.2
5G User Equipment 2 RX	89.9465	50.0000	106	1268.2

Table 8.1. Terminals location - Short range communications.

Link	Data Rate [Mbit/s]	BS height above Ground RX [m]	UE height above Ground TX [m]	Dist. from BS 1 [m]	Eb/N0	Link marg.	TIREM losses along Meteor crater[dB]	Eb/N0
UE_{TX} - BS_{RX}	10	10	2	108	63.316	20	10.1068	33.209
BS_{TX} - UE_{TX}	10000	10	2	106	69.762	20	10.1068	39.655

Table 8.2. Short range communication link results.

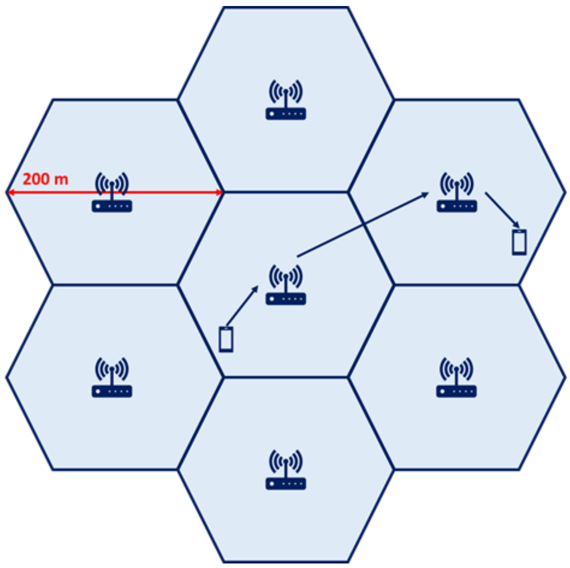

Figure 8.2. Possible link between two User Equipments inside two different 5G lunar network cells - Long range communications.

LUNAR SITE	Shackleton Crater			
	Coordinate		Distance from Base Station 1 [m]	Terrain height [m]
	Latitude[°]	Longitude [°]		
5G Base Station 1 RX	-89.9500	50.0000	0	1257.7
5G Base Station 3	-89.9670	50.0000	51 6	1243.2
5G User Equipment 1 TX	-89.9707	50.6603	627	1240.7
5G User Equipment 2 RX	89.9465	50.0000	106	1268.2

Table 8.3. Terminals location - Long range communications.

Link	Data Rate [Mbit/s]	BS height above Ground RX [m]	UE height above Ground TX [m]	Dist. from BS 1 [m]	Eb/N0	Link marg.	TIREM losses along Meteor crater[dB]	Eb/N0
UE_{TX} - BS_{RX}	10	10	2		53.349	20	10.1068	23.243
BS_{TX} - BS_{RX}	10000	10			68.158	20	0	48.153
BS_{TX} - UE_{RX}	10000	10	2		69.762	20	10.1068	39.655

Table 8.4. Long range communication link results.

The results confirmed what was previously observed and the two links were closed and highly reliable.

Future studies can focus on the use of the TIREM module combined with the lunar terrain, if this feature is developed by AGI, or try to take it into account with the use of new software and / or algorithms. In addition, in the coming years they will be able to count on more precise information about the Artemis program, currently in the design phase, and on the first results obtained by Nokia during the tests it will conduct on the lunar soil with 4G / LTE technology.

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