Future Lunar Surface Network Study

Final Project Report – Unlimited Data Rights

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1 Introduction

Nokia of America Corporation (Nokia) powered by the research and innovation of Nokia Bell Labs, is honored to have been asked by NASA to conduct a Systems Engineering and Integration (SE&I) study to evaluate an Initial Operating Capability (IOC) for a 3rd Generation Partnership Project (3GPP)-based future lunar surface communication network for the Artemis Program. In particular, the SE&I study has focused on developing an architecture and a 3GPP-based network solution that meets the requirements of the Artemis V mission and at the same time can be evolved and expanded to meet the needs and requirements of future missions in the Moon to Mars program.

Nokia strongly believes that 3GPP-based communications and networking solutions present the most effective and future-proof technological path for advanced lunar surface communications (and beyond) for the next decades. 3GPP technologies (whether 4G, 5G or 6G in the future) have revolutionized voice, video, and data transmissions on Earth in consumer, enterprise, and industrial applications, and continue to enable significant gains in productivity, efficiency, and safety. The same benefits can be harnessed for space missions and the future lunar economy including, but not limited to the Artemis program. 3GPP technologies will revolutionize lunar surface communications by increasing data-rates, reducing latency, and providing critical voice, video and data communication capabilities across large surface areas while meeting the stringent reliability requirements of human-rated space flight missions.

These technologies, in particular 4G/LTE and 5G/NR, are mature and proven technologies that are being used by billions of users, sensors, and machines every day and benefit from large economies of scale with global operators investing more than $100 billion annually on 4G / 5G. The massive size of the commercial market supports the multi-billion-dollar research and development investments made in these technologies over decades by the telecommunications industry. These investments have resulted in a large ecosystem of technology, component, and software suppliers. The underlying information systems support highly efficient and scalable deployment scenarios with multiple standards-compliant radio frequencies, flexible bandwidth allocations, scalable high data rates, energy efficient transmission power control and a large number of end terminals. 3GPP networks are built on robust Orthogonal Frequency Division Multiplexing (OFDM) technologies that provide protection against multi-path and are highly efficient in their use of the available radio frequency spectrum. Being a cellular network technology, 3GPP natively supports mobility from stationary and fixed users to highly mobile users with seamless data handovers between multiple radio base stations. In short, 3GPP-based network solutions enable multiple high-speed, low-latency, high-reliability proximity communications.

NASA's current baseline communication technologies for lunar surface communications are generations behind the most advanced 3GPP capabilities used every day on Earth. Lunar surface communication systems still rely heavily e.g., on UFH-based technologies with a small number of voice channels, extremely low bandwidth (measured in hundreds of kbps), with virtually no video support and limited coverage range of approximately 1-2km within line of sight. Wi-Fi is being considered for short-range non-critical communications because of its higher throughputs, general availability, and ease of use. Wi-Fi, however, has a limited reliable range, inadequate communication assurance and overall limited scalability.

The next logical step is to leverage the advanced 3GPP communication solutions for the lunar surface and connect astronauts, LTV rovers, pressurized rovers, cameras, and sensors. It is of course understood that any networking solution developed and deployed on the lunar surface needs to be reliable and secure, withstand the harsh environmental conditions, and be optimized for size, weight, and power.

Nokia Bell Labs began the development of an E2E 4G/LTE solution for space in 2018 based on a commercially available Nokia wireless small cell product. In 2020, NASA selected Nokia to deploy the first 4G/LTE network on the lunar surface via the Tipping Point program. Leveraging the expertise and accumulated knowledge from earlier activities and together with Intuitive Machines (provider of the Nova-C lander and Hopper spacecraft) and Lunar Outpost (provider of the MAPP Rover), the mission is scheduled to launch later in 2024 to the lunar South Pole to prove the viability of 4G/LTE as critical-communication capability and to gather performance data to calibrate existing RF propagation models in support for future missions.

3GPP is the only single networking technology currently available that can support all the mission requirements for the Artemis program. In this SE&I study, Nokia provides a very comprehensive analysis of the 3GPP technologies with a detailed architecture and solution overview and articulates how 3GPP can satisfactorily meet all the requirements from the communication performance, SWaP, reliability, and environmental hardening perspectives.

2 Executive Summary

Nokia, with the support and guidance of NASA, has conducted a Systems Engineering and Integration (SE&I) study for a 3GPP-based lunar surface network to address the communication and application needs for future Artemis missions. The study has focused on the development of a plan, with the corresponding technical analysis, for achieving a baseline initial operating capability (IOC) for 3GPP-based extra-vehicular activity (EVA) communications in the Artemis V timeframe. The following conclusions are achieved:

1. 3GPP-based technologies can meet the critical communication requirements for Artemis V and beyond in terms of number of users, data-rates, latency, reliability/criticality, and coverage for voice, video, and data applications.
2. No other commercially available technology can meet all the above requirements simultaneously.
3. A 3GPP-based network can be engineered, built, and deployed into SWaP-optimized space products and solutions that leverage a commercial, standards compliant, ecosystem rich and proven technology suite that is used by hundreds of millions of people, devices, and machines worldwide.
4. Like in any major technology breakthrough programs, there are risks associated with it. We have identified those risks and corresponding mitigations that lead us to believe that the Artemis V 3GPP IOC program can be accomplished successfully.
5. A stepwise integrated approach, with carefully planned and executed DTOs in Artemis III and Artemis IV along with intermediate terrestrial testing, is recommended to gradually increase the TRL of the proposed 3GPP network solution, minimize risks and culminate with the Artemis V IOC deployment.
6. From the regulatory aspect, the recommended spectrum from SFCG 32-2R5, exceeds the needs for a 3GPP deployment in the Artemis V timeframe.

3 Technical Summary

This section summarizes the main technical outcomes and recommendations from the study. Detailed assessments and information are found in the corresponding report sections.

- An end-to-end (E2E) solution architecture and use cases with corresponding 3GPP network capabilities is recommended. This includes:
    - A 3GPP Network in a Box (NIB) on both the HLS and the LTV.
    - 3GPP UEs in the Astronaut suits.
    - An optional 3GPP UE on the LTV for LTV-specific requirements and ConOps.
- An assessment of key 3GPP radio access and core network functionalities that support the use cases and requirements has been provided:
    - Both LTE and 5G NR can meet or exceed the mobile broadband communication requirements for the initial Lunar surface communication network.
    - Both LTE and 5G NR can be implemented in an architecture appropriate for deployed Lunar surface communications.
    - The LTE capacity can be increased by deploying more RF carriers within each NIB, or by deploying multiple NIBs. Proper network planning would be needed for future network expansions.
    - 5G NR seems to be more future proof for Lunar surface network expansion but:
        - Its scalability and performance benefits are not required in the Artemis V scenarios explored.
        - The scalability and performance benefits may negatively impact SWaP.
    - The following minimum standard releases are recommended: Rel.12 for LTE, Rel.15 for 5G and Rel.17 for 5G SideLink.
    - The final choice of LTE or 5G NR as a starting point needs to be made by weighing the tradeoffs above against other Artemis details and priorities of NASA. That said, Nokia recommends that, within the early to mid-2030’s, NASA should plan to utilize 5G regardless of its initial implementation choice.
    - Further, Nokia recommends that NASA adopts a communication plan where the version of 3GPP used is no more than 1 1/2 – 2 generations behind the global 3GPP commercial plans.

- A distributed 3GPP-network Operations and Maintenance (O&M) framework, including a security assessment, is presented:
    - The O&M software should be custom designed for the use cases and take into account specific requirements of managing small scale telecom networks that provide critical services at remote and inaccessible locations.
    - High delay, limited data rates, potentially constrained availability, and specific communication protocols on the links to Earth should all be factored in the architecture and operational framework for O&M services.
    - All elements of the communication system (NIBs, UE and O&M) need to be developed in conjunction with each other and cannot be developed in isolation of each other without the risk of significant issues, interoperability and standards-compliant testing or large integration efforts. Having the service designed and implemented with strong E2E security features in place is also recommended.
- The Artemis voice application has a few distinguishing and challenging requirements:
    - The need to maintain local voice conferencing for Moon participants during disconnection from the main conference is unique. In order to provide a seamless voice experience, the key challenge is fast network convergence, followed by fast application convergence.
    - The Earth-Moon link presents two significant challenges. First, its availability and loss profile are highly dissimilar to a typical Earth or Moon surface link. Second, it has a disproportionally large latency that makes interactive voice difficult.

- A video architecture is proposed with the following recommendations:
    - Real-time video will transit LunaNet over Direct-to-Earth links (DTE) and leverage the networking solutions implemented for voice communications.
    - The LunaNet interfaces are ideal control points for video services utilizing the Delay-Tolerant-Network (DTN) aspects of LunaNet.
    - The video bitstream syntax can be constrained to help maintain the quality through transmission and to mitigate error effects.
    - H.264 is a viable video codec except at lower bitrates where H.265 performs much better.

- From the Hardware (HW) Engineering perspective:
    - NIB Implementation:
        - A NIB SWaP-optimized architecture is presented leveraging existing terrestrial building blocks both for 4G and 5G.
        - Using space grade components implies a power consumption / dissipation increase which may result in a size/mass increase too, negatively affecting SWaP.
        - It is strongly recommended to quickly start the further characterization of some commercial-off-the-shelf (COTS) components, especially custom SoCs, to evaluate their performance and their ability to meet the reliability requirements. This hybrid approach can potentially have a positive impact on SWaP and development costs.
    - UE Implementation:
        - Two high-level architectures for designing a 3GPP UE solution for Artemis V are presented.
        - Given the complexity and integration level of the UE modem's SoCs and the significant annual R&D investment and expertise needed, it is unrealistic to build a cellular modem from scratch based on space graded / rad-hardened FPGAs and expect a similar level of performance, interoperability, SWaP and the feature rich capability set of a commercial cellular modem SoC.
        - We recommend the use of a commercial modem SoC. That said, we also recommend that a detailed characterization of their performance and tolerances be started as soon as possible.
        - In terms of Device to Device (D2D) communications, it is recommended that 5G SideLink be considered for astronaut-to-astronaut communications given its benefits, functionality/capability set and ability to operate side-by-side with the network-based communication mode.
        - Existing UHF solutions in EVA suits are recommended to be maintained in the first Artemis missions to provide a back-up communications link.
    - RF Antennas Implementation:
        - Different antenna concepts are evaluated that can be designed and built according to specifications.
        - UE antenna placement might be challenging and limit performance. Detailed designs are for further study with the EVA suit provider.

        - NIB antenna architectures for 360 deg coverage around the HLS can be implemented to support both short range and long-range scenarios.

- In terms of network performance, detailed Radio Frequency (RF) planning and 3GPP-based localization/positioning capabilities analyses have been performed.
    - Predicted SNR and data-rates support communications to 10 km.
    - The communication range is highly dependent on the chosen landing site and surrounding terrain.
    - While there are coverage gaps in certain areas or traverses, the feasibility of realistically being able to traverse those areas in a mission is evaluated by means of terrain slope analysis.
    - The Nokia Bell Labs fast propagation modeling tool (or a similarly capable alternative) that takes a digital terrain map as an input and generates the predicted path gain for the area Lunar surface communication coverage analysis is essential to support future lunar mission planning.
- HW and SW reliability considerations, critical to human-rated spaceflight, have been evaluated in detail including key identified gaps with respect to telecom industry practices.
    - It is recommended to implement hardware redundancy for both the NIB and UE. This is open to further scrutiny during the low-level system architecture and design phase.
    - It is recommended to procure space qualified parts as much as possible, with additional upscreening and/or selective testing as required. However, there will be impacts on SWaP due to the switch from COTS components.
    - Any components not on the DoD/NASA approved lists may need to be re-finished.
    - While a UE modem chipset may have some space/radiation tested components available, additional component level and system level radiation testing will be needed to characterize and mitigate impacts from radiation. It is recommended to start a radiation test program as soon as possible.
    - SW verification of underlying code running in FPGAs and SOCs can be quite costly and takes a lot of time.
    - It is recommended to verify and trace SW that is specifically built for the space missions, i.e. additional requirements, and their implementation.

    - A comprehensive end-to-end SW integration and testing plan is expected to be implemented, including provocative test cases and corner-case scenarios to ensure that the end-to-end system performance is according to the requirements.
- A spectrum and frequency planning assessment, based on existing frequencies per SFCG 32-2R5, is provided.
    - The available frequencies (2.505GHz to 2.655GHz and 3.5GHz to 3.8GHz) appear sufficient for accommodating the requirements and use cases for the Artemis V mission.
    - For future expansion, and depending on the use cases and requirements, adding additional bands could be beneficial, especially considering future capabilities such as multi-band deployments or surface relay links.
    - The impossibility to use frequencies below 2GHz due to radio astronomy constraints poses limitations on adding a standard 3GPP band. If more spectrum is needed, some possibilities could be:
        - Extend the upper bound of the 2.6GHz band to achieve higher FDD bandwidths.
        - Use of the spectrum around 5GHz (with high frequency performance penalties in coverage). However, coexistence with Wi-Fi needs to be addressed.
- Security / FIPS considerations
  - Today's 3GPP standards do not include AES-256 link encryption. Requiring AES-256 link encryption would deviate from 3GPP and could cause significant interoperability and compatibility issues between the network elements (NIB) and UEs.

    Based on certification lab wait lists and schedules, a FIPS Cryptographic Module Validation Program (CMVP)[1] certification alone impacts the schedule, not accounting for FIPS-compliant system development costs and schedule impacts. FIPS CMVP certification and/or revalidation is per product/product release.

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[1] More information at: https://csrc.nist.gov/projects/cryptographic-algorithm-validation-program

4 End-to-end system architecture

4.1 Design Principles

In order to meet the requirements and use cases presented by NASA, a number of key design principles and criteria had been carefully selected:

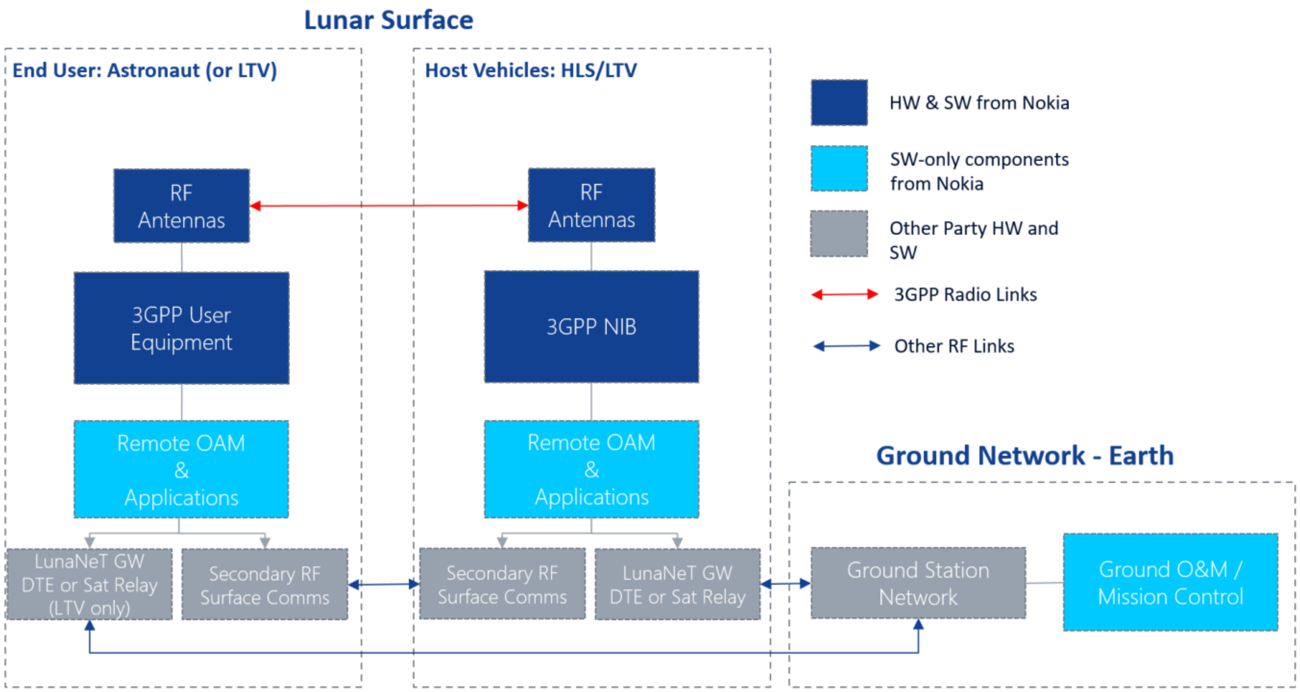
- The 3GPP lunar network should meet the initial operative capability (IOC) requirements with minimum complexity while the architecture should be expandable and scalable to meet future use cases and requirements.
- Each 3GPP lunar network node is assumed to contain all network elements to be able to provide fully autonomous and independent coverage areas on the lunar surface.
- The HLS and LTV are endpoints for 3GPP traffic.
- Interoperability shall be maintained between the lunar surface 3GPP network and other integrated technologies and architectures, based on LunaNet recommendations and blueprints.
- IP is the baseline integration protocol with the HLS and LTV.
- Every link may fail (e.g., DTE, Orbiting Relay, 3GPP Surface Comms), so the network architecture and overarching solutions need to be resilient to that.
- Coverage and data-rates need to be qualified with RF simulations for each selected landing area or location on the lunar surface.
- The networking layer is transparent to the application layer.

4.2 High-level architecture

Figure 1 depicts the high-level system architecture of the proposed 3GPP lunar surface network. Further details on capabilities will be provided in the following sections as detailed use cases are described. The presented architecture and design are technology (LTE or 5G) and frequency agnostic. Details on the proposed technology and frequency recommendations are provided in Section 11.

We are segmenting the main lunar surface 3GPP network components in two main areas: network elements that are integrated and hosted by spacecrafts such as the HLS and LTV and network elements that are integrated into the astronaut's EVA suit (end user). As it will be described later, we will consider one additional use case in which the end user is also the LTV.

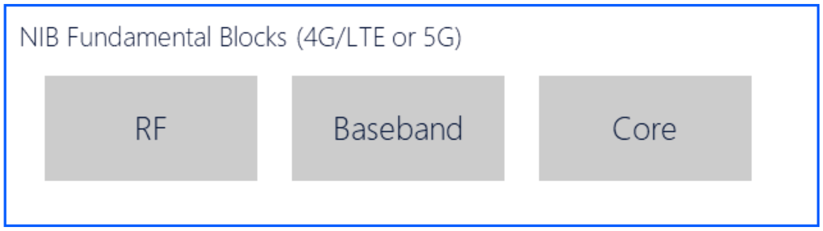
Figure 1. High-level system architecture



4.2.1 Network in a Box (NIB) definition

The fundamental network element of the proposed 3GPP lunar network is the NIB. Figure 2 depicts the main building blocks of the modular and expandable 3GPP NIB being proposed. The fundamental NIB capabilities correspond to the key elements that are required to enable 3GPP-based surface communications, which compromise the Radio Frequency (RF), Baseband and Core network functionalities. As it was mentioned in **Section 4.1** , it is proposed that each NIB operates independently of each other with full operational capability.

Figure 2. Modular NIB building blocks



4.3 Use Cases and Evaluated Scenarios

Multiple scenarios based on NASA's envisioned requirements have been analyzed, broken down in different sub-scenarios and evaluated with corresponding 3GPP network capabilities.

These scenarios are:

1. HLS EVA walk
2. LTV EVA
3. Emergency walk-back

4.3.1 Scenario 1: HLS EVA walk

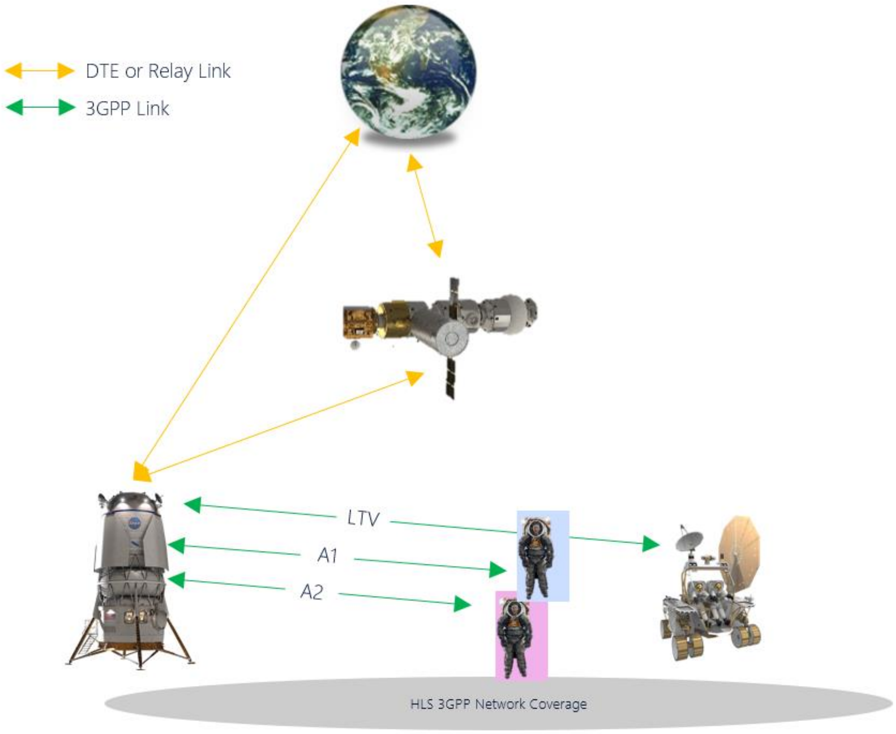
In this scenario, up to two astronauts (represented in blue and pink background colors) are performing EVA activities around the HLS. The resulting 3GPP network and architecture to meet this scenario consists of:

- A 3GPP NIB is hosted on the HLS.
- Each EVA suit has a 3GPP User Equipment (UE).
- To enable LTV communications via the HLS, an additional 3GPP UE hosted on the LTV can be considered.
- The IP termination point for the 3GPP lunar network is in the HLS.

The resulting nominal data path for this scenario is as follows:

- Astronaut/LTV-to-HLS via 3GPP Surface Communication NIB.
- HLS-to-Earth via DTE or Orbiting Relay.
- Should one astronaut lose their coverage to the HLS, but the second one is in coverage of the HLS, relay comms is enabled via the 3GPP SideLink.
- Should both astronauts lose their coverage to the HLS, Astronaut-to-Astronaut (A-to-A) comms is enabled via the 3GPP SideLink.

Figure 3. Scenario 1 diagram



4.3.2 Scenario 2: LTV EVA

In this scenario, up to two astronauts are performing EVA activities around LTV. The resulting 3GPP network and architecture to meet this scenario consists of:

- A 3GPP NIB is hosted on the LTV.
- Each EVA suit has a 3GPP UE.
- The IP termination point for the 3GPP lunar network is on the LTV.

The resulting nominal data path for this scenario is as follows:

- Astronaut-to-LTV via 3GPP Surface Communications.
- LTV-to-Earth via DTE or Orbiting Relay.
- Should one astronaut lose their coverage to the LTV, but the second one is in coverage of the LTV, relay comms is enabled via 3GPP SideLink (see **Figure 5**).
- Should both astronauts lose their coverage to the LTV, A-to-A comms is enabled via 3GPP SideLink (see **Figure 6**).

In this scenario, it is assumed that, as soon as the astronauts are ready to embark on the LTV, the LTV-hosted NIB is powered up and astronauts' UEs are automatically registered and connected to the LTV 3GPP NIB.

Figure 4. Scenario 2 diagram

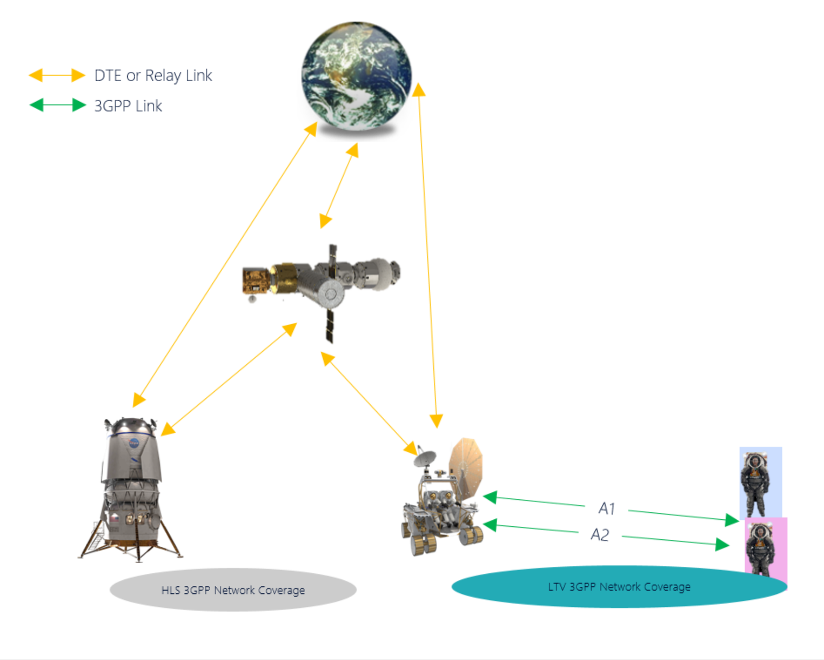


Figure 5. Scenario 2 diagram (with SideLink relay)

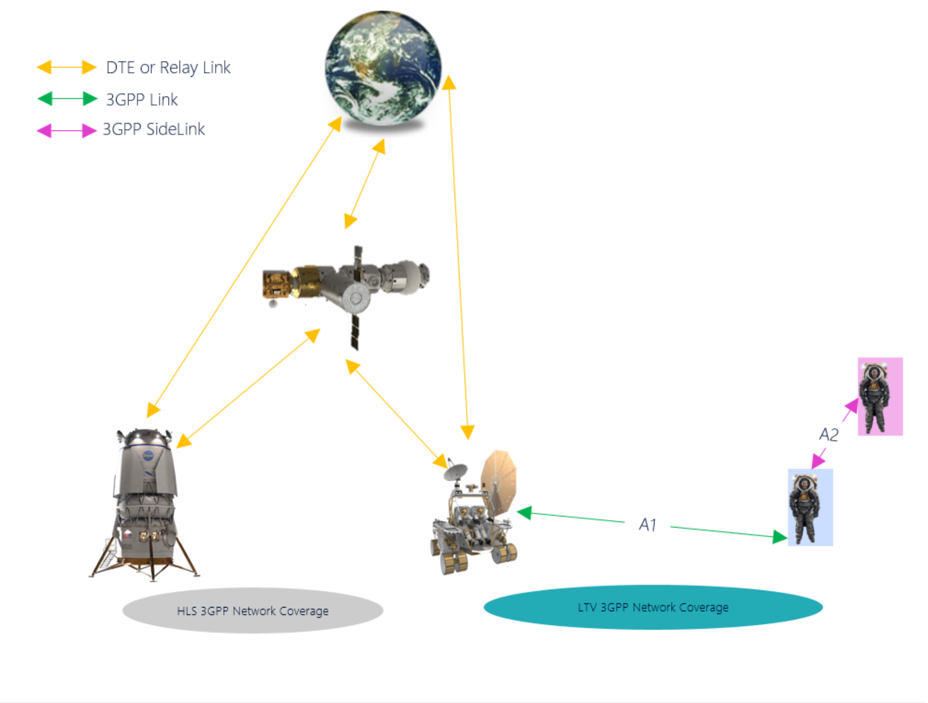
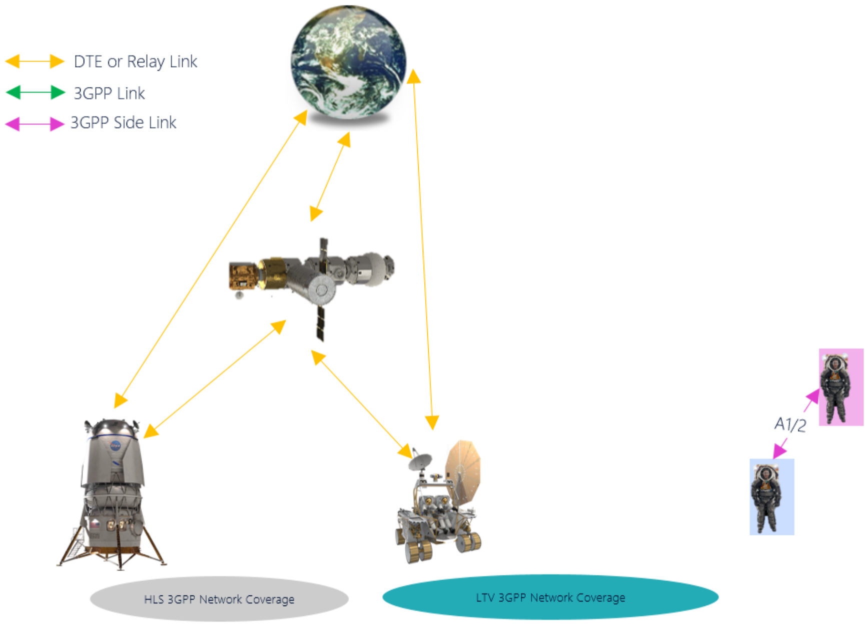


Figure 6. Scenario 2 diagram (A-A via SideLink)



4.3.3 Scenario 3: Emergency walk-back

In this scenario, up to two astronauts who were performing EVA activities around the LTV, need to execute an emergency walk-back due to a failure on the LTV. It is then expected that the 3GPP UEs will hand over to the HLS hosted 3GPP network when in range of the HLS 3GPP network. The resulting 3GPP network and architecture to meet this scenario consists of:

- A 3GPP NIB hosted on the HLS.
- Each EVA suit has a 3GPP UE.
- The IP termination point for 3GPP lunar network is on the HLS.

The resulting nominal data path for this scenario is as follows:

- Astronaut-to-HLS via 3GPP Surface Communications.
- HLS-to-Earth via DTE or Orbiting Relay.
- Should one astronaut lose their coverage to the HLS, but the second one is in coverage of the HLS, relay comms is enabled via 3GPP SideLink (see **Figure 8**).
- Should both astronauts lose their coverage to the HLS, A-to-A comms is enabled via 3GPP SideLink (see **Figure 9**).

In this scenario, it is assumed that astronauts can hand over to the HLS 3GPP network at long distances; this will be shown to be feasible when discussing the performance of the 3GPP network.

Figure 7. Scenario 3 diagram

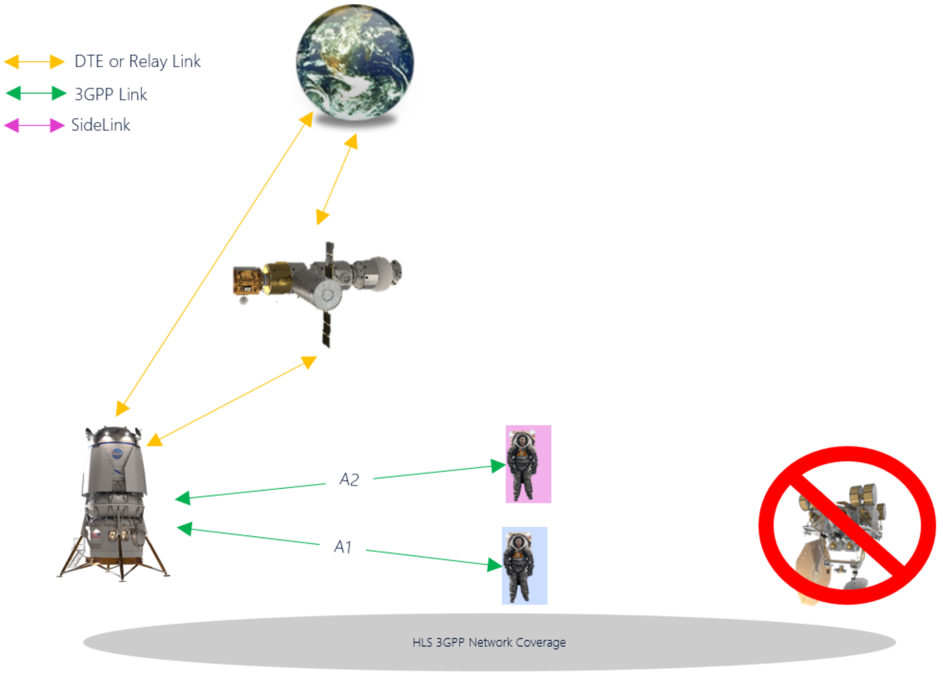


Figure 8. Scenario 3 diagram (with SideLink relay)

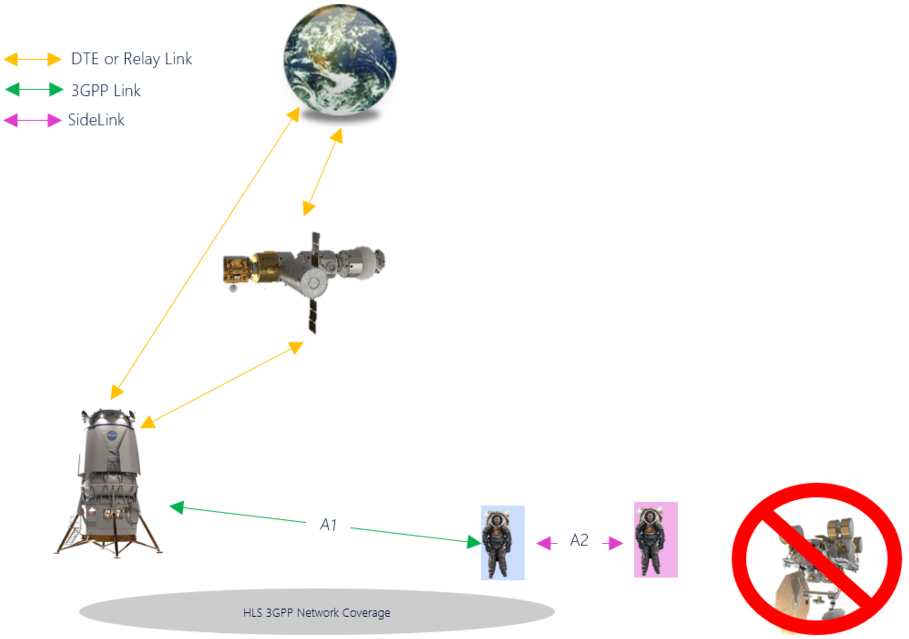
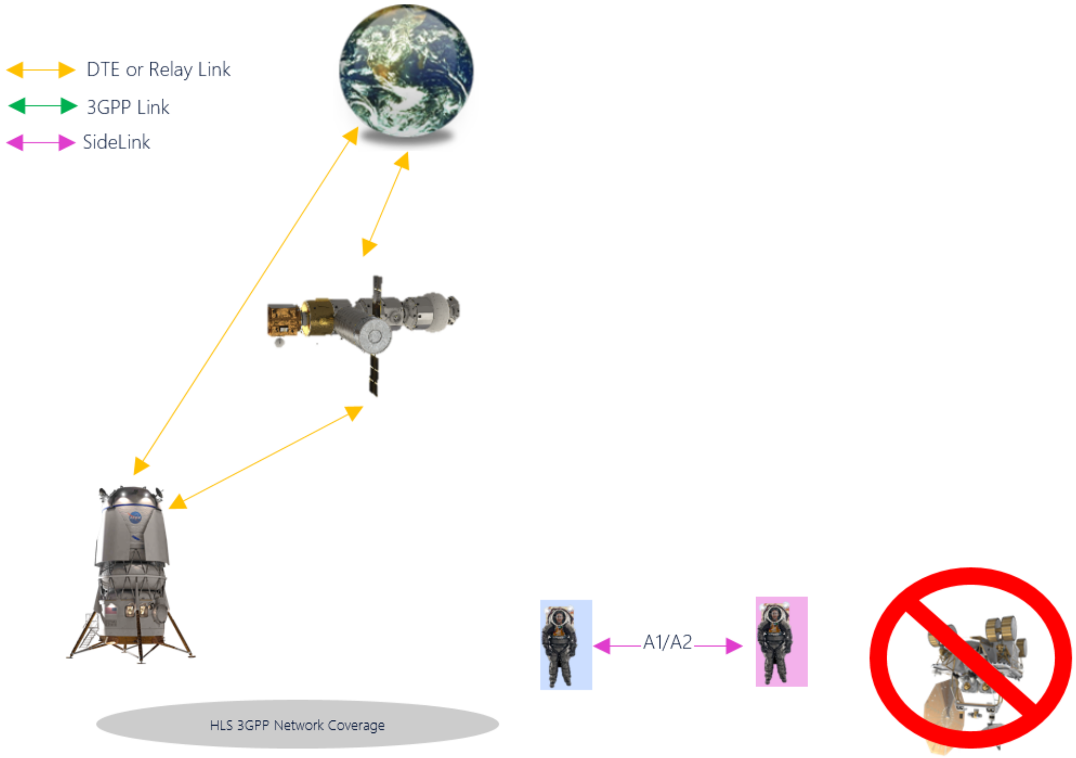


Figure 9. Scenario 3 diagram (A-A via SideLink)

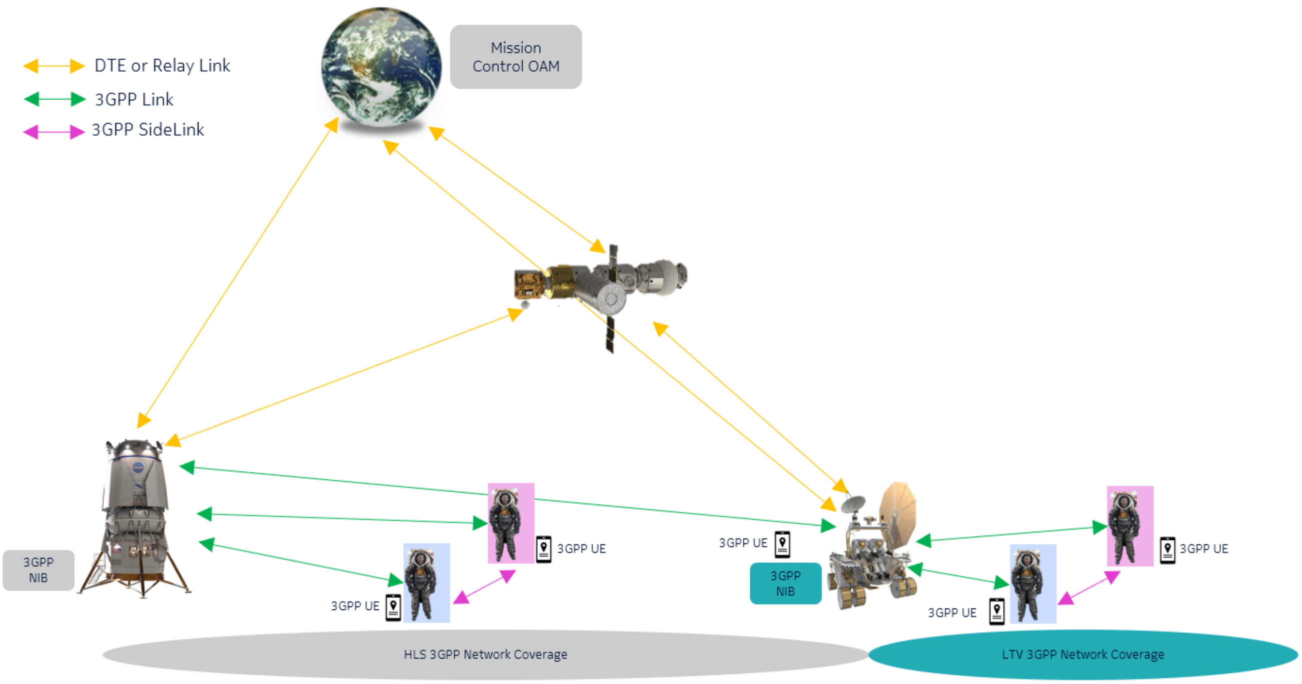


4.4 Consolidated 3GPP Network Architecture

Based on the evaluated scenarios and ConOps discussed in the previous sections, an all-encompassing 3GPP network architecture is depicted in **Figure 10** below. The key characteristics of this solution are:

- Each host vehicle (HLS and LTV) will integrate a 3GPP NIB.
- Each 3GPP NIB will provide independent 3GPP coverage areas around the host vehicles.
- Each 3GPP NIB will interface with LunaNet gateways and DTE/Relay links on the host vehicles.
- Each 3GPP NIB will be self-contained and be able to operate in isolation of other 3GPP NIBs, therefore eliminating points-of-failure (compared to e.g., some NIBs having partial functionality and relying upon other NIBs for full operation).
- Each astronaut will integrate a 3GPP UE that enables them to connect to the closest 3GPP NIB and will also feature 3GPP SideLink functionalities for astronaut-to-astronaut direct or relay communications.
- The LTV can also integrate a 3GPP UE for LTV-centric data communications via the HLS 3GPP network.

Figure 10. Consolidated 3GPP Network Architecture



4.5 Interoperability and integration considerations

3GPP lunar surface networks shall be interoperable with other networking technologies and be compatible with the LunaNet architecture and blueprints. In addition, it is of utmost importance to maintain 3GPP standards compliance to avoid any proprietary technology lock-in and ensure that an ecosystem of stakeholders and devices can leverage the communication capabilities of the proposed 3GPP solution.

It is therefore recommended that:

- The main host vehicles (HLS and LTV) act as endpoints for the 3GPP network traffic and perform LunaNet gateway functions to the space segment.
- To ease integration efforts, it is recommended that the main integration protocol is IP..
- The base station and Core Network (integrated into the NIB), and the UE must be 3GPP certified and have proven interoperability. Normally, both RAN/Core vendors and UE vendors execute extensive interoperability testing campaigns to ensure 3GPP standards compliance and seamless interoperability.

In terms of integration requirements, the following services and capabilities are required for the 3GPP network:

- Thermal management and thermal power to ensure the 3GPP NIB and 3GPP UEs remain within the operational and survival temperature ranges.
    - From the 3GPP NIB perspective and depending on the integration requirements with the host vehicles (HLS or LTV), radiator solutions can be designed to be implemented as part of the 3GPP NIB thermal-mechanical solution.
- Data interfaces to 3GPP NIB and 3GPP UE.
    - Ethernet protocol interface as the main application data interface is recommended.
    - RS-422 serial interface or similar as an additional interface for control is recommended.

5 Radio Access and Core

5.1 Key requirements and assumptions

Below is the set of key requirements and assumptions for the Artemis V IOC deployment that determine the solution described in subsequent sections. These are not hard limits on the proposed architecture, but reference points to derive the minimum set of requirements.

1. All-in-one Network-In-a-Box (NIB) architecture.
2. Available RF bands according to SFCG 32-2R5.
3. Up to 2 astronauts doing EVA activities.
4. Each EVA helmet camera sources one 1080p (FHD) or 4K video stream at 30fps using an HEVC encoder resulting in 3-12Mbps.
5. No more than 4 cameras are operating simultaneously. This could be either 2 helmet cameras and 2 remote EVA (handheld) cameras or 2 helmet cameras and 2 LTV cameras.
6. EVA suit can relay audio and telemetry data from other EVA suits that do not have line-of-site to the host. It is assumed that relayed voice traffic has priority over any video traffic.
7. The peak data rates for each EVA suit are:
    a. DL: < 1Mbps
    b. UL single camera: ~13Mbps max
    c. UL double camera: ~26Mbps max
8. The peak data rates for the communication between the HLS and the LTV are:
    a. DL: < 1Mbps
    b. UL: ~22Mbps
9. The NASA provided data rates are at the application layer. A 10% overhead is added for the physical layer data rates.
10. Audio QoE class is provided according to ANSI S3.2.
11. Command and telemetry data packet loss rate is < 1e-6.
12. Other data packet loss rate is < 1e-5.
13. The audio data packet delay is < 100ms.

The following sections describe the minimum required 3GPP User Equipment (UE), Radio Access Network (RAN) and Core Network capabilities that support the use cases and requirements for Artemis V.

5.2 UE Capabilities

The “capabilities” are an essential part of every 3GPP UE. “Capabilities” define supported features including band, carrier aggregation, band combinations, etc. All UE features are included in the UECapabilityIndication message (exchanged between UE and RAN). (3rd Generation Partnership Project, 2023) and (3rd Generation Pathnership Project, 2023) define the capabilities parametrization for LTE and NR respectively. This report only covers a subset of critical “capabilities” needed to meet the Artemis V requirements, such as data-rates and carrier aggregation. For more details we refer to the above specification documents.

5.2.1 Key LTE UE capabilities for Lunar surface communications

For the UE category, this document will focus only on the UE Category in UL, reported with *ue-CategoryUL* type of fields.

Table 1 - Uplink parameters set by *ue-CategoryUL*

UE UL Category	3GPP Release	Maximum number of UL-SCH transport block bits transmitted within a TTI	Maximum number of bits of an UL-SCH transport block transmitted within a TTI	Support for 64QAM in UL	Support for 256QAM in UL
UL Category M1 (Note 1)	13	1000 or 2984	1000 or 2984	No	No
UL Category M2	14	6968	6968	No	No
UL Category 0	12	1000	1000	No	No
UL Category 1bis	14	5160	5160	No	No
UL Category 3	12	51024	51024	No	No
UL Category 5	12	75376	75376	Yes	No
UL Category 7	12	102048	51024	No	No
UL Category 8	12	1497760	149776	Yes	No
UL Category 13	12	150752	75376	Yes	No
UL Category 14	13	9585664	149776	Yes	No
UL Category 15	13	226128	75376	Yes	No
UL Category 16	14	105528	105528	Yes	Yes
UL Category 17	14	2119360	211936	Yes	Yes
UL Category 18	14	211056	105528	Yes	Yes
UL Category 19	14	13563904	211936	Yes	Yes
UL Category 20	14	316584	105528	Yes	Yes
UL Category 21	14	301504	75376	Yes	No
UL Category 22	15	422112	105528	Yes	Yes
UL Category 23	15	527640	105528	Yes	Yes
UL Category 24	15	633168	105528	Yes	Yes
UL Category 25	15	738696	105528	Yes	Yes
UL Category 26	15	844224	105528	Yes	Yes
🟩	- UL 2CC CA + 64QAM capable UE				
🟦	- UL 2CC CA + 256QAM/64QAM capable UE				

The most important capabilities needed to meet the requirements in Section 5.1 are listed below:

- LTE Uplink Carrier Aggregation

To fully utilize 2CC Carrier Aggregation in Uplink, UL Category 13 would be required.

- LTE 64QAM and 256QAM in UL

Whether the UE supports 64QAM or/and 256QAM is clearly indicated by UE UL Category. UL Category 13, already listed as UL CA capable, supports also 64QAM in the uplink, but does not support 256QAM.For the QAM256 and 2CC Uplink Carrier Aggregation, Table 1 marks with blue color the UE categories that support both.

Key takeaway: Only certain types of UEs can be considered for Lunar surface communication because of their support for mandatory features.

5.2.2 Key NR UE capabilities for Lunar surface communications

In the case of NR terminals, there is no concept of UE categories. Instead, each individual capability is explicitly reported. Also, maximum supported data rates are not reported explicitly. Such information can be calculated using the equation, specified in (3rd Generation Pathnership Project, 2023), in Section 4.1.2. This formula has been used to calculate peak data rates in section 5.3.4.3. The most important capabilities are described is subsequent sections.

For every *supportedBandListNR* structure (see (3rd Generation Pathnership Project, 2023)), structure channelBWs-DL or/and channelBWs-UL indicates the UE supported channel bandwidths for each subcarrier spacing. For FR1, different channel bandwidths are reported by the UE. Indirectly, the UE reports support for 100MHz natively.

The supported modulation order and MIMO support can be reported separately for each subcarrier spacing and direction (DL/UL) structures for downlink and uplink respectively.

For the downlink, the maximum number of MIMO layer parameters needs to be checked for specific subcarrier spacing (SCS).

For the uplink, the supported modulation and MIMO structure needs to be checked, as codebook-based transmission in the uplink direction is mandatory for the UE to be supported.

Key takeaway: Certain fields in the UE capabilities are required for Lunar surface communication, depending on the selected features:

- **If a channel bandwidth different than 100 MHz is desired, it should be checked if the desired bandwidth is supported by the UE.**
- **QAM64 is supported natively. QAM256 is reported separately for each direction (DL/UL).**

5.3 Radio Access Technology

5.3.1 NIB synchronization and timing requirements

To maintain proper level of operation, a 3GPP-based network requires synchronization between different nodes. There are several types of synchronization:

- Frequency synchronization – the frequency of the radio frame clock is the same as the frequency of the reference signal.
- Phase synchronization – both the frequency and the start of the frames in the radio interface are phase synchronized to a time reference source.

Frequency synchronization is sufficient for Frequency Division Duplex (FDD) 3GPP radio transmission, while phase synchronization is needed for Time Division Duplex (TDD) radio transmission, to be able to synchronize user data transmissions in the DL and UL between nodes as well as to avoid interference.

From the 3GPP standards perspective, the radio network timing and synchronization requirements[2] are:

- Frequency synchronization requirements: +-0.1ppm per 3GPP 36.104 Section 6.5.1.
- Phase synchronization requirements (for TDD systems): <10us per 3GPP 36.133 Section 7.4.

The above requirements are generally met by terrestrial network equipment via:

- GPS/GLONASS input or
- IEEE 1588 PTP signal input.

A Precision Time Protocol solution must conform to the following Telecom Profiles:

- G.8265.1 Precision Time Protocol Telecom Profile for Frequency Synchronization.
- G.8275.1 Precision Time Protocol Telecom Profile for Phase/Time Synchronization with Full Timing Support from the Network.

The above 3GPP requirements translate into the following lunar surface timing requirements to be provided to the lunar 3GPP NIB:

- A PNT receiver at the host vehicles (HLS and LTV) that outputs the following signals: GPS-like output or IEEE 1588 PTP.
- If a PNT receiver is not available, a 10MHz reference clock could for example be considered for the timing and synchronization source for the 3GPP NIB.

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[2] Note that the 3GPP UE gets synchronization from the 3GPP network.

5.3.2 Key aspects of 3GPP-based Lunar Surface network

5.3.2.1 Number of users

As the initial Lunar surface network deployments are expected to be very small, the number of users is not going to be an important factor in terms of capacity and performance. The initial number of active UEs is assumed to be less than 10 in the Artemis V, VI, and VII missions but the architecture and solutions can accommodate a larger number of users.

Traffic profile and data rates requirements

There are several types of communication applications anticipated for the Lunar network:

- Voice communication between astronauts on the surface or/and mission control center with low bi-directional traffic and data rates of less than 1Mbps.
- Telemetry data from space vehicles and astronauts with low uplink traffic and data rates of less than 1Mbps.
- Video sent from cameras mounted on either the EVA suits or vehicles down to Earth with high uplink traffic and data rates up to 12Mbps for each camera.

Based on the above listed use cases, this type of network is highly uplink demanding and centric, unlike the majority of typical terrestrial mobile networks, which are downlink centric.

Based on the data rate requirements listed in Section 5.1 and required use cases below, the overall generated maximum data rate estimation is calculated.

<u>Scenario #1:</u> 3GPP coverage – HLS, UEs – LTV, 2xEVA: 3GPP Network coverage provided by the NIB installed on HLS, UE installed on LTV and astronaut's space suits.

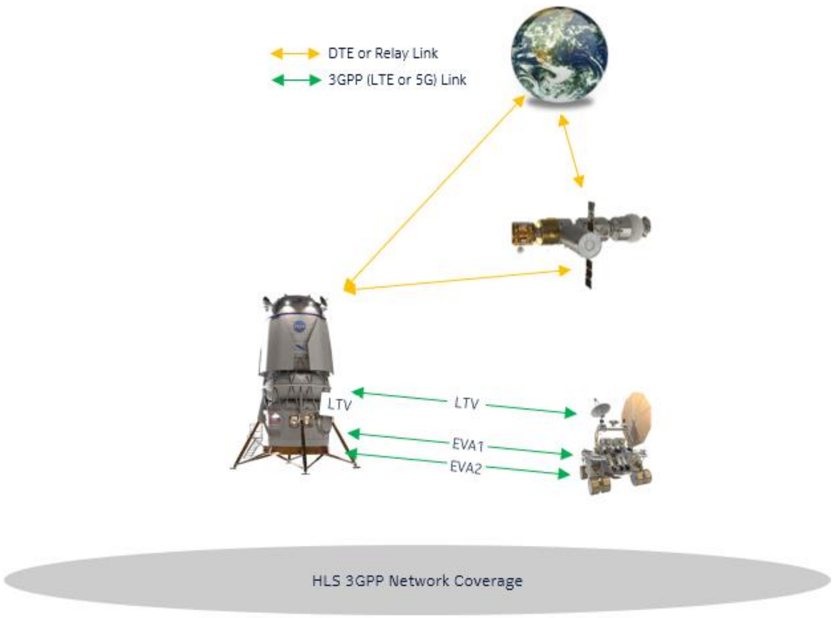

Figure 11 - 3GPP Network deployment - Scenario #1

Table 2 - Data rates estimate for Scenario #1

	DL data rates (kbps)	**UL data rates (Mbps)**
Maximum	~400	(13*2 + 22) * 1.1 = ~53
Minimum	~400	(3*2 + 7) * 1.1 = ~14

Scenario #2: 3GPP coverage – HLS and LTV separately, UEs – 2xEVA: 3GPP Network coverage provided by the NIB installed on both HLS and LTV, User Equipment installed on astronaut's space suits. In this scenario, it is assumed that both astronauts UEs are connected to the same vehicle NIB, in this case LTV.

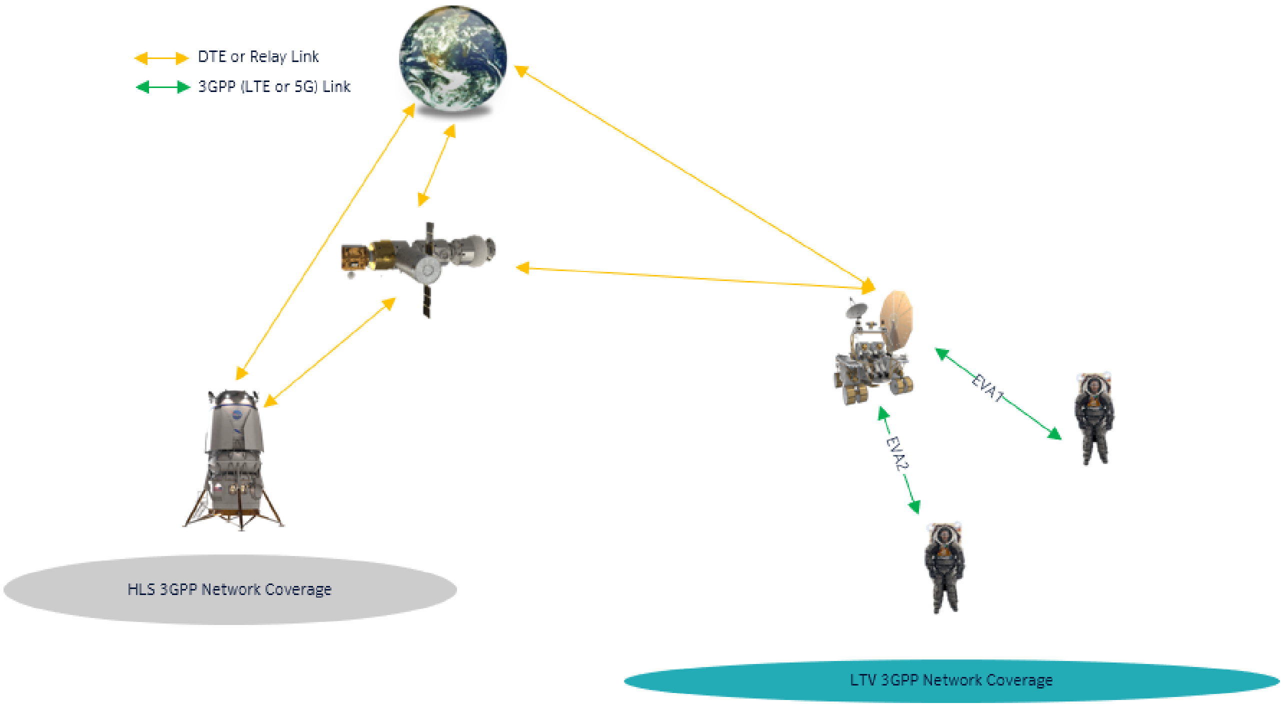

Figure 12 - 3GPP Network deployment - Scenario #2

3GPP Network coverage provided by the NIB installed on both HLS and LTV, User Equipment installed on astronaut's space suits. In this scenario, it is assumed that both astronauts UEs are connected to the same vehicle NIB, in this case LTV.

Table 3 - Data rates estimate for Scenario #2

	DL data rates (kbps)	**UL data rates (Mbps)**
Maximum	~200	13*2 * 1.1 = ~29
Minimum	~200	3*2 * 1.1 = ~7

Scenario #3: 3GPP coverage – HLS and LTV using 3GPP-based wireless backhaul towards HLS, UEs – 2xEVA: This future scenario is beyond Artemis V-VII plan but is depicted here for analysis completeness. All EVAs are connected to LTV hosted 3GPP network. All traffic from LTV, including own traffic and from two astronaut suites is relayed over 3GPP-base UE relay on LTV towards HLS.

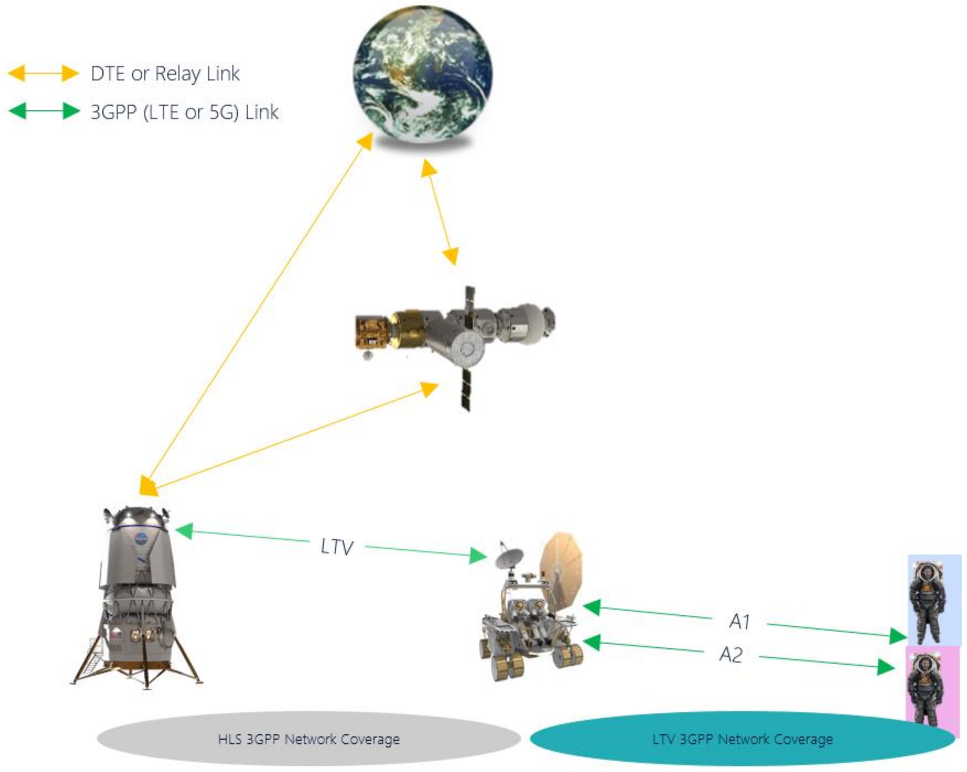

Figure 13 - 3GPP Network deployment - Scenario #3

Table 4 - Data rates estimate for Scenario #3

	DL data rates (kbps)	**UL data rates (Mbps)**
Maximum	~400	(13*2 + 22) * 1.1 = ~53
Minimum	~400	(3*2 + 7) * 1.1 = ~14

Key takeaway: User traffic on Lunar surface is uplink dominant. The most demanding data rates for the NIB are:

- **DL: < 1 Mbps**
- **UL: ~ 53 Mbps**

5.3.2.1.1 NASA's peak data rates requirements vs 3GPP

A simple comparison of the data rates required in this study with the 3GPP theoretical peak data rates is provided in the following tables for the uplink and downlink, respectively.

Table 5 - Uplink peak data rates; NASA requirement vs. 3GPP achievable[3]

	NASA requirement	3GPP Rel8 single RF carrier FDD 20MHz	3GPP Rel10 2CC CA FDD (20MHz + 10MHz)	3GPP Rel8 single carrier (20MHz) TDD Frame Config 0	3GPP Rel10 2CC CA TDD (20MHz + 20MHz) Frame Config 0	3GPP Rel15 TDD 100MHz UL:DL 4:6
UL peak data rate, 64QAM [Mbps]	53	69.95	104.18	39.22	78.44	166.0
UL peak data rate, 256QAM [Mbps]	53	100.02	149.68	65.79	131.58	221.4

Table 6 - Downlink peak data rates; NASA requirement vs. 3GPP achievable

	NASA requirement	3GPP Rel8 single RF carrier FDD 20MHz	3GPP Rel10 2CC CA FDD (20MHz + 10MHz)	3GPP Rel8 single carrier (20 MHz) TDD Frame Config 0	3GPP Rel10 2CC CA TDD (20MHz + 20MHz) Frame Config 0	3GPP Rel15 TDD 100MHz UL:DL 4:6
DL peak data rate, 64QAM [Mbps]	1	147.2	218.61	50.81	101.63	412.7
DL peak data rate, 256QAM [Mbps]	1	191.35	286.6	67.18	134.37	564.1

5.3.2.2 Band allocation

According to (Space Frequency Coordination Group, 2023), and as discussed in Section 11, the best candidates for the spectrum allocations that can be used for Lunar surface communication are:

- 2503.5 MHz – 2655.5 MHz – B7/N7 (FDD, up to 35 MHz BW), B38/N38 (TDD, up to 40MHz), B41/N41 (TDD, up to 151.5 MHz)

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[3] PxSCH L1 peak data rates with 1% retransmission, DL MIMO 2x2, No UL MIMO, 1 PDCCH symbol

- 3500.0 MHz – 3800.0 MHz –B48 (TDD, up to 150 MHz), N77/N78 (TDD, up to 300 MHz))

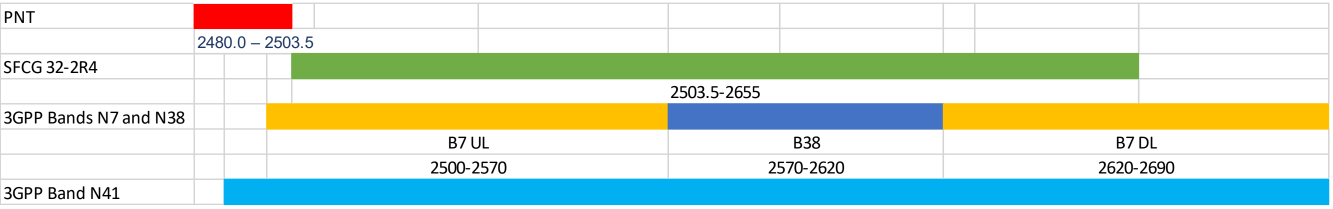

Figure 14 - Spectrum availability in 2.5 GHz range

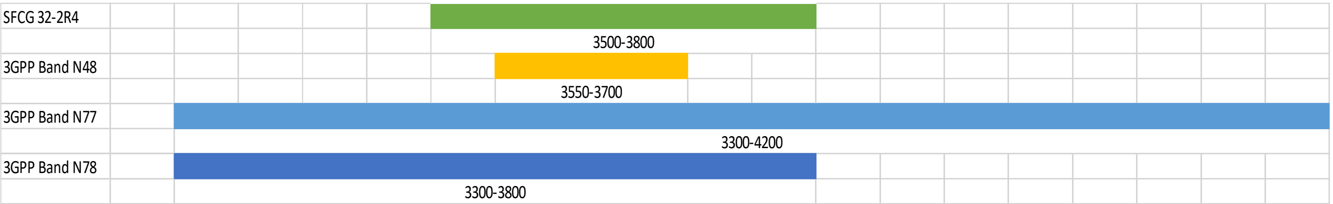

Figure 15 - Spectrum availability in 3.5 GHz range

As indicated in the previous section, the lunar traffic profile is highly asymmetrical, with much heavier uplink traffic demand (up to 53Mbps UL) compared to the downlink traffic demand (less than 1 Mbps DL) per NIB. For such scenarios, using paired FDD spectrum is not optimal, as it would waste available downlink spectrum. Based on Figure 14, instead of using B7 FDD, it would be more optimal to utilize the frequency range of B41 and enable the option of having multiple RF carriers within B41.

In case of LTE as the access technology, it is recommended to use 2.5GHz band, and B41 TDD particularly, which is wide enough to support multiple carriers if needed.

Key takeaway: B41 TDD band is most suitable for an LTE network on the Moon. B7 FDD can be an alternative spectrum option. Due to the anticipated current asymmetrical traffic profile, if TDD is not chosen, the spectrum will not be used in the most efficient way. For 5G NR, either N41 or N78 bands can be utilized.

5.3.3 LTE as Radio Access Technology for Lunar communication

5.3.3.1 Key LTE features for the Lunar communication

5.3.3.1.1 Voice services

The LTE network can support voice services in two ways:

- Voice over LTE with a dedicated service that requires support both from the network and the devices, in which connections are managed using the Session Initiation Protocol (SIP) with an IP Multimedia Subsystem (IMS).
- Over The Top (OTT) software clients which use regular data connections. They do not require any specific functionalities from devices, nor the network.

The baseline voice codec is G.711 with Pulse Code Modulation (PCM) of voice frequencies (ITU-T, 1993), which are then carried using either the VoLTE solution, or the OTT application.

The protocol stack belonging to the VoLTE service is illustrated in Figure 16. The speech data itself passes through RTP, UDP and IP layers before reaching the radio access layers (PDCP, RLC, MAC and Layer 1). In parallel to the speech data protocol stack, there are RTCP and SIP protocol stacks. The RTCP layer at the receiver is responsible for collecting statistics regarding the quality of the received speech signal. These statistics are sent back to the transmitting device where they can be used to adapt the transmitted signal, e.g., step down to a lower codec rate when the received signal quality is poor. The RTCP signaling is transferred across the same bearer as the speech data, i.e., the RTP and RTCP layers operate in parallel on the same bearer. The SIP protocol stack runs in parallel to the RTP and RTCP protocol stacks. SIP is transferred using its own bearer and is used for signaling with IMS when establishing and releasing VoLTE connections.

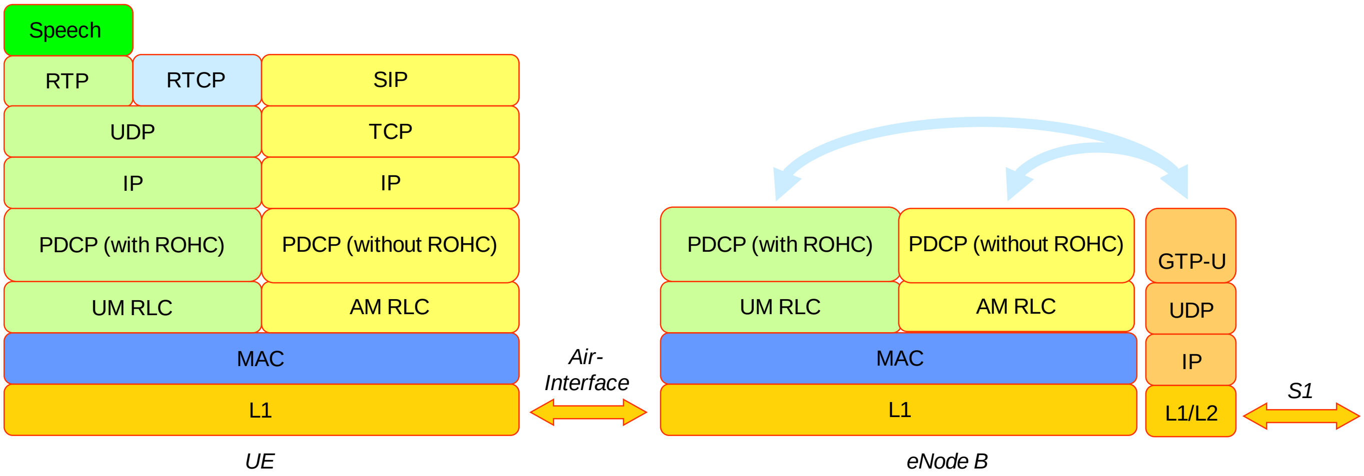

Figure 16 - Protocol stack for VoLTE service

The protocol stack illustrated in Figure 16 uses 2 bearers. The RTP and RTCP combination are transferred using a QCI1 bearer (GBR), whereas SIP is transferred using a QCI5 bearer (non-GBR). These bearers are shown in Table 7. The GBR bearers are treated differently by both Admission Control and the Packet Scheduler. They are prioritized over non-GBR bearers which are typically associated with non-real time applications. SIP uses a non-GBR bearer but also uses a flag to indicate that the content is signaling and has relatively high priority.

Table 7 - Characteristics associated with QCI1 to QCI9 bearers

QCI	Type	Priority	Packet Delay Budget	Packet Error Loss Rate	Example Services
1	GBR	2	100 ms	10^{-2}	Conversational Voice
2		4	150 ms	10^{-3}	Conversational Video
3		3	50 ms	10^{-3}	Real Time Gaming
4		5	300 ms	10^{-6}	Non-Conversational Video (buffered)
5	Non-GBR	1	100 ms	10^{-6}	IMS Signalling
6		6	300 ms	10^{-6}	Video (buffered), TCP based
7		7	100 ms	10^{-3}	Voice, Video, Gaming
8		8	300 ms	10^{-6}	Video (buffered), TCP based
9		9			

The combination of low connection throughput and the RTP/UDP/IP protocol stack means that the overheads generated by the various headers can be significant and can more than double the bit rate generated by the codec. This increases the importance of header compression when using the VoLTE service. Header compression helps to avoid having to transfer large overheads across the air-interface. Header compression is provided by the PDCP layer which can compress the RTP, UDP and IP headers.

There are various optional features which aim to improve the coverage and capacity of the VoLTE service:

Semi-Persistent Scheduling (SPS)

SPS uses a combination of persistent and dynamic scheduling. Persistent scheduling is used to allocate periodic resources which are intended for the first transmission of transport blocks.

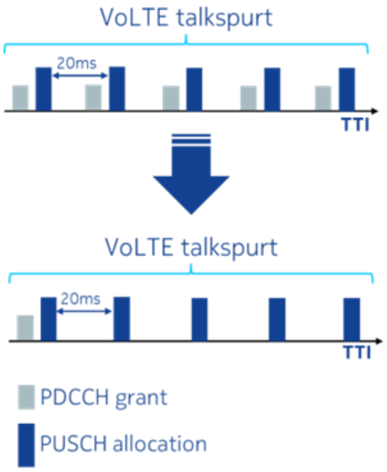

Figure 17 - Semi-Persistent scheduling overview

Dynamic scheduling is used to allocate resources for re-transmissions, as and when required. SPS is suitable for applications like VoLTE because the packets arrive periodically, i.e., VoLTE packets arrive once every 20 ms. The use of persistent scheduling reduces the PDCCH capacity requirement because it is no longer necessary to make individual resource allocations for every packet transmission. The general idea of SPS is presented below:

The main benefit is an increased number of handled VoLTE users, when PDCCH is highly utilized, on high traffic scenarios.

TTI Bundling

TTI bundling is intended to improve the uplink coverage performance of VoLTE, i.e., improve air-interface performance in scenarios where coverage is limited by the UE transmit power. Each uplink VoLTE transport block is passed to the physical layer of the UE where it has CRC bits added before being channel coded. Four duplicates of the channel coded transport block are generated prior to rate matching. Each duplicate is processed using a different Redundancy Version (RV). This provides the eNodeB receiver with an Incremental Redundancy soft combining gain. The set of four codewords are modulated and mapped onto four consecutive uplink subframes which generates an effective TTI duration of 4 ms, as presented on Figure 18. The four consecutive TTI define the bundle size which is fixed by 3GPP. There is an impact upon PDSCH capacity because four subframes rather than one subframe are used for each transmission.

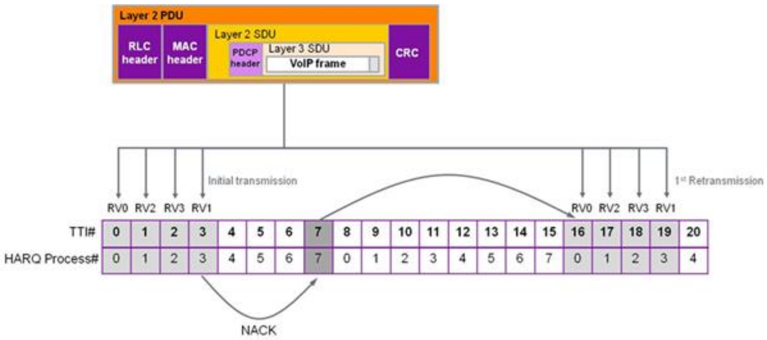

Figure 18 - TTI bundling overview

Packet Aggregation

Packet aggregation can be applied in both the uplink and downlink directions. It helps to improve the capacity of the PDCCH, PDSCH and PUSCH. The drawback of using packet aggregation is increased delay but the packet scheduler operates to ensure that the target delay budget is achieved. VoLTE packets arrive at the lower layers once every 20 ms. Packet aggregation means that two or more packets are grouped before transmitting across the air-interface, e.g., if two packets are grouped then VoLTE packets are transmitted across the air-interface once every 40 ms instead of once every 20 ms. This reduces the PDCCH load by a factor of 2 because the number of resource allocations is halved. It also makes the PDSCH and PUSCH more efficient because one larger packet is transferred rather than two small packets.

Layer 2 Segmentation

Layer 2 segmentation is intended to improve the uplink coverage performance of VoLTE (same objective as TTI bundling). Each VoLTE packet is segmented into two or more sections. These sections of the original packet are transferred across the air-interface during separate subframes. This reduces the throughput requirement per subframe and so improves the uplink link budget. The PDCCH load is increased because multiple resource allocations are required for each VoLTE packet. Similarly, the PUSCH load is increased because the PUSCH is occupied for multiple subframes.

5.3.3.1.2 VoLTE capacity

The maximum number of users within a cell can be limited by the PDCCH, PDSCH, PUSCH, PHICH or PUCCH. Typical calculations confirm that even for 1.4MHz LTE cell bandwidth maximum number of VoLTE users is ~50. With this study, the projection is to have ~10 UEs, and cell BWs wider than 1.4MHz.

Key takeaway: For the required number of users in the lunar scenarios, the anticipated cell capacity is sufficient.

5.3.3.1.3 VoLTE vs. Over The Top VoIP solution

Native VoLTE requires support from both devices and network. It adds additional significant complexity to the EPC / 5GC, by adding SIP and IMS functionality. On the other hand, there is no limitation to use QCI1 dedicated bearer for both voice data and signaling traffic, also optionally enabling additional features listed above. To simplify the whole network architecture, Nokia's recommendation is to use an Over-the-Top VoIP solution using dedicated QCI1 bearer for voice related traffic, with specific QoS parameters.

It should be noted that some VoLTE related features have some interdependencies with Carrier Aggregation features, coming from either 3GPP specification or vendor's implementation.

5.3.3.2 Frame configuration – FDD vs. TDD considerations

Data transmission occurs in time slots defined as frames. The frame structure considers only the time domain. Two frame structures, called "Type 1" and "Type 2" have been specified in 3GPP TS 36.211 (3rd Generation Partnership Project, 2023). Frame structure 'Type 1' applies to FDD, for both downlink and uplink transmissions. A single 10 ms radio frame is divided into 10 subframes of 1 ms each. Each 1 ms subframe is then divided into two slots of 0.5 ms each.

Since FDD is a paired spectrum, it has dedicated bandwidth separately for downlink and uplink transmissions. This implies that for the uplink transmission full bandwidth can be utilized, as opposed to TDD.

Frame structure 'Type 2' applies to TDD. Like frame structure 'Type 1', a single 10 ms radio frame is divided into 10 subframes of 1 ms each. Each frame is then divided into two half-frames of 5 ms each. Subframes can be either downlink, uplink, or special. Special subframes are used when switching from downlink to uplink, but not when switching from uplink to downlink.

RAN vendors may only support a subset of 3GPP-defined supported subframe configurations. The selection of the uplink and downlink subframe configuration has a direct impact upon the capacities of the PDSCH and PUSCH, resulting in the peak data rates achievable. Since the Lunar use cases under study are uplink demanding, a frame configuration and a special subframe configuration that support higher uplink transmissions should be chosen.

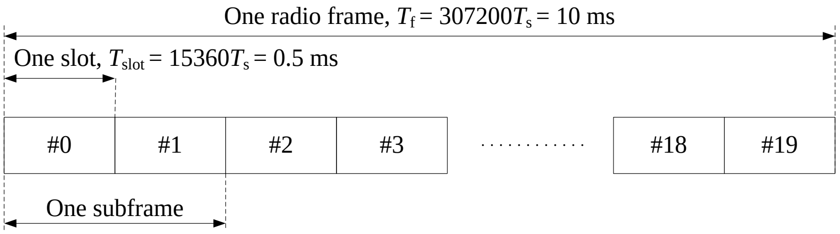

Figure 19 - Frame structure 'Type 1'

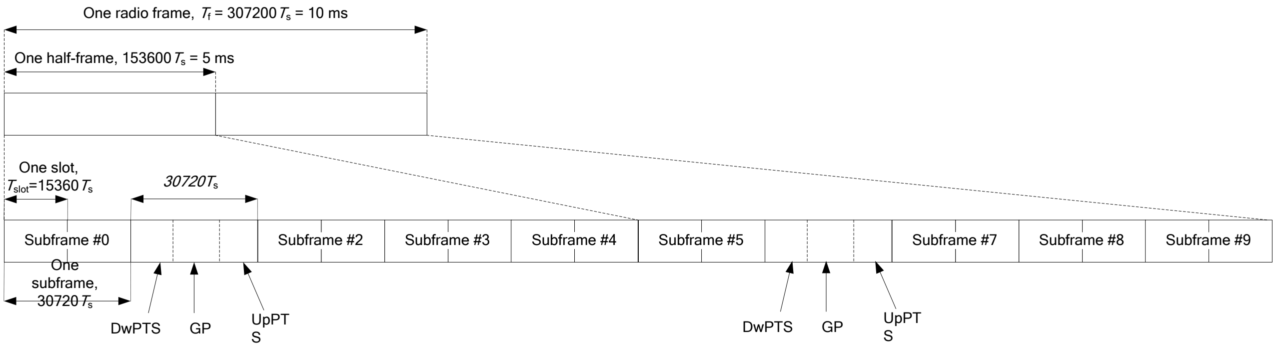

Figure 20 - Frame structure 'Type 2'

5.3.3.3 TDD downlink peak data rates

Examples of the theoretical downlink peak data rates achievable for LTE TDD technology are presented in Table 8 below:

Table 8 - TDD DL theoretical peak data rates for 2x2 MIMO and 64QAM/256QAM

DL L1 peak Throughput (0% BLER) depending on TDD Frame Configuration 1 or 2 [Mbps], TM3/4 2x2				
UE Category	**BW**	**Modulation**	**Throughput**	
			Frame Configuration 1	**Frame Configuration 2**
8	**5 MHz**	**64QAM**	-	-
	10 MHz		39.83	54.51
	15 MHz		59.56	81.58
	20 MHz		80.96	111.11
14	**5 MHz**	**256QAM**	-	-
	10 MHz		52.71	72.29
	15 MHz		80.55	110.70
	20 MHz		**106.34**	**145.50**

5.3.3.4 TDD uplink peak data rates

Examples of the uplink theoretical peak data rates are presented in Table 9 below:

Table 9 - TDD UL theoretical peak data rates

UL L1 peak Throughput (0% BLER) depending on TDD Frame Configuration 0, 1 or 2 [Mbps]					
UE Category	**BW**	**Modulation**	**Throughput**		
			Frame Configuration 0	**Frame Configuration 1**	**Frame Configuration 2**
8	**5 MHz**	**64QAM**	8.53	-	-
	10 MHz		17.29	9.78	4.68
	15 MHz		28.13	13.60	6.80
	20 MHz		**39.22**	**20.20**	**10.00**
19	**5 MHz**	**256QAM**	13.22	-	-
	10 MHz		32.73	13.48	6.45
	15 MHz		49.05	18.76	9.38
	20 MHz		**65.79**	**27.99**	**13.77**

As can be seen, in ideal radio conditions, the highest possible data rate is achievable with Frame Configuration 0 and higher modulation such as 64QAM, or even 256QAM.

5.3.3.5 Uplink Carrier Aggregation

Carrier Aggregation (CA) increases the channel bandwidth by combining multiple RF carriers, called Component Carriers (CC). It is applicable to both downlink and uplink directions, and to both FDD and TDD. However, in the case of TDD, the uplink-downlink subframe configuration for all CC must be the same. The primary aim of this feature is to boost the mean and peak user throughputs by sending user data simultaneously over two or more Component Carriers. There are three general types of Carrier Aggregation scenarios defined by 3GPP:

- Intra-band contiguous
- Intra-band non-contiguous
- Inter-band non-contiguous

Actual use of the Carrier Aggregation functionality requires several conditions:

- The NIB has to be properly configured, with two cells being configured, and the feature activated and the proper relation between the cells defined.
- The operating band and channel bandwidths of the cells to be aggregated need to be reported by the UE in the UE Capability Information message.
- Certain conditions regarding Admission Control and data in the buffers need to be met.

Recommendation (Space Frequency Coordination Group, 2023) regarding possible band allocations for Lunar surface communication lists band B41 (between 2503.5Mhz-2655MHz) as suitable for this purpose.

5.3.3.6 Conclusions

- LTE TDD NIB(s), operating in B41, are configured with Uplink/Downlink Subframe Configuration for UL-dominant traffic.
- With a limited number of users, the control channels will not be limiting the capacity of the NIB.
- Voice type of services can be realized using Over-the-Top (OTT) software clients, using QCI1/QCI5 QoS classes to simplify network architecture.
- Voice service-related features described in this section can be used optionally, but they are not mandatory given the requirements of the lunar scenarios.

5.3.4 NR as Radio Access Technology for Lunar communication

5.3.4.1 Key NR features for the Lunar communication

5.3.4.1.1 Voice services

Voice communication is an essential service offered by mobile service providers. It is the pillar of any wireless radio technology. Voice communication is provided by an IMS core for Voice over LTE (VoLTE) and Voice over New Radio (VoNR). To establish a voice call within a PS domain two bearers are needed: one for IMS signaling (5QI5) and another one for voice data itself (5QI1). 5QI1 can be established together with or after 5QI5 is set up. Before 5QI1 is set up, the gNB verifies if UE is VoNR capable After the Initial Context Setup procedure, AMF may send NGAP UE Radio Capability Check Request to the gNB. As per 3GPP, this procedure is triggered by AMF whenever it needs to verify if UE radio capabilities are compatible with the network configuration for IMS voice. Next, when voice communication is needed for a UE already registered in the IMS, the 5QI5 DRB is used for SIP signaling to request a voice call setup for the UE, which results in sending PDU Session Modification Request from AMF to setup 5QI1 QoS flow. Establishment of both, 5QI5 and 5QI1/5QI2 together, may occur when the UE connects the cell due to HO with VoNR/VoNR call ongoing.

VoNR, similarly to VoLTE, requires IP Multimedia Subsystem (IMS) for SIP signaling, which adds extra complexity to the 5G Core Network.

Over The Top (OTT) VoIP solution can also be taken into consideration, utilizing existing 5QI Quality of Service (QoS) classes, to handle voice signaling and data. For more details on voice solutions, see Chapter 6.2.

5.3.4.2 Radio frame structure

In 5G New Radio (NR), the TDD frame configuration has been defined in a more flexible way than with LTE.One of the new 5G NR functionalities, compared to LTE, is the ability to support multiple, so called, numerologies, in other words, multiple subcarrier spacings, defined in (3rd Generation Partnership Project, 2023). Subcarrier spacing (SCS) is based on common 15kHz for FDD and 30kHz for TDD.

Figure 21 - Subframe structure for numerology μ=1

The selection of the numerology has direct implications on the radio structure that is used for transmission. Each radio frame duration is 10 ms, which is divided into 10 subframes, of 1 ms each, regardless of the numerology, as defined in (3rd Generation Partnership Project, 2023). Then depending on the numerology, each subframe is divided into slots. An example is presented on Figure 21.

In NR, symbols within a slot can be configured in different combinations, predefined in (3rd Generation Partnership Project, 2023) chapter 11. From this study requirements, frame structure should be UL dominant, based on data rates requirements listed in 5.1.

Example of such configuration is presented on below picture:

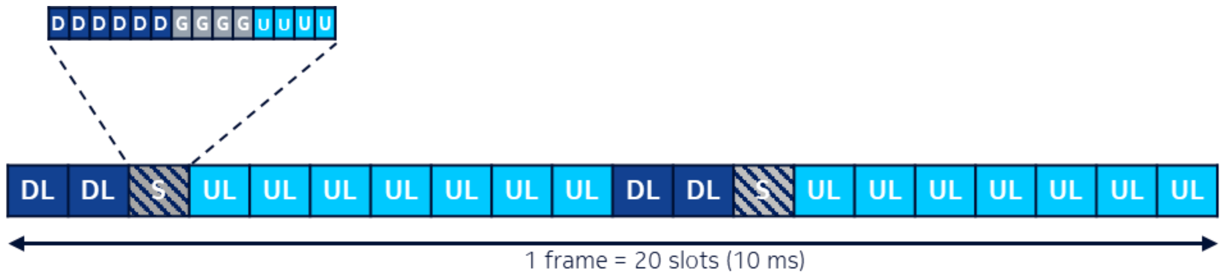

Figure 22 - Example of UL dominant frame NR frame structure

5.3.4.3 Peak data rates

The tables below present examples of peak data rates with specific frame configurations, with different MIMO and modulation options.

Table 10 - Example peak data rates for 4:6 with DL MIMO 4x4, UL MIMO 2x2, QAM256

Common configuration	Cell specific configuration	DL peak throughput	UL peak throughput
• TDD Frame structure 4:6 • Cell Deployment: SA • Bandwidth: up to 100MHz • FDM Scheduling: TRUE • DL MIMO: 4x4 • UL MIMO: 2x2 • DL/UL modulation: 256QAM	BW 20 MHz	**177 Mbps**	**32 Mbps**
	BW 30 MHz	**274 Mbps**	**82 Mbps**
	BW 40 MHz	**351 Mbps**	**146 Mbps**
	BW 50 MHz	**440 Mbps**	**180 Mbps**
	BW 60 MHz	**536 Mbps**	**223 Mbps**
	BW 70 MHz	**622 Mbps**	**258 Mbps**
	BW 80 MHz	**719 Mbps**	**298 Mbps**
	BW 90 MHz	**807 Mbps**	**333 Mbps**
	BW 100 MHz	**912 Mbps**	**376 Mbps**

Table 11 - Example peak data rates for 4:6 with DL MIMO 2x2, UL MIMO 1x1, QAM256

Common configuration	Cell specific configuration	DL peak throughput	UL peak throughput
• TDD Frame structure 4:6 • Cell Deployment: SA • Bandwidth: up to 100MHz • FDM Scheduling: TRUE • DL MIMO: 2x2 • UL MIMO: 1x1 • DL/UL modulation: 256QAM	BW 40 MHz	**175 Mbps**	**73 Mbps**
	BW 50 MHz	**220 Mbps**	**90 Mbps**
	BW 60 MHz	**269 Mbps**	**112 Mbps**
	BW 70 MHz	**311 Mbps**	**129 Mbps**
	BW 80 MHz	**357 Mbps**	**149 Mbps**
	BW 90 MHz	**404 Mbps**	**166 Mbps**
	BW 100 MHz	**456 Mbps**	**189 Mbps**

Table 12 - Example peak data rates for 4:6 with DL MIMO 2x2, UL MIMO 1x1, QAM64

Common configuration	Cell specific configuration	DL peak throughput	UL peak throughput
• TDD Frame structure 4:6 • Cell Deployment: SA • Bandwidth: up to 100MHz • FDM Scheduling: TRUE • DL MIMO: 2x2 • UL MIMO: 1x1 • DL/UL modulation: 64QAM	BW 40 MHz	**129 Mbps**	**54 Mbps**
	BW 50 MHz	**163 Mbps**	**69 Mbps**
	BW 60 MHz	**198 Mbps**	**83 Mbps**
	BW 70 MHz	**232 Mbps**	**98 Mbps**
	BW 80 MHz	**265 Mbps**	**112 Mbps**
	BW 90 MHz	**300 Mbps**	**126 Mbps**
	BW 100 MHz	**334 Mbps**	**140 Mbps**

Key takeaway:

- **NR NIB(s) should be operating in bands N41 or N78.**
- **The minimum configuration that meets NASA's requirements is a tradeoff between the channel bandwidth, the maximum supported MIMO order and the radio frame structure.**
- **Voice type of services can be realized using Over-the-Top (OTT) software clients, using 5QI1/5QI5 QoS classes.**

5.3.5 LTE vs. NR consideration

5.3.5.1 LTE advantages/disadvantages for Lunar communication

The advantages of LTE technology for the Lunar surface communication are:

1. Mature technology and largely deployed in terrestrial networks.
2. Stable 3GPP specifications.

The disadvantages of LTE technology for Lunar surface communication are:

1. Limited margin of scalability in terms of uplink peak data rates with increased number of users (vehicles, or astronauts). Note that based on the current understanding of mission requirements this does not appear to be an issue through at least Artemis VII.
2. ProSe is not expected to be commercialized in LTE. If using LTE from the NIB, the UEs would need to support both LTE and 5G which is common in commercial devices today.

5.3.5.2 NR advantages/disadvantages for Lunar communication

The advantages of NR technology for the Lunar surface communication are:

1. Significantly over provisioned to support increased number of users and future services not yet defined without major changes in the recommended architecture.
2. Additional security features beyond LTE.
3. Supports larger number of radio bands, including FR2, which (Space Frequency Coordination Group, 2023) also recommends as suitable for Lunar surface communication.
4. The current trajectory indicates that SideLink will be commercialized.

The disadvantages of NR technology for Lunar surface communication are:

1. Initial terrestrial deployments of 5G NR base stations are focused on Enhanced Mobile Broadband (eMBB) use cases, end-user experiences, and extremely high capacity (number of users), with implied macro gNB solutions. Macro gNB’s are not suitable for Lunar network because they are significantly over dimensioned in terms of capacity and more importantly, in terms of SWaP.
2. More complex algorithms in the user-plane data processing require more processing power, which may imply increased power consumption when compared. to LTE.
3. A more complex 5G Core Network requires more processing power.
4. Commercial deployments of 5G SA (5G with a standalone mode for the core) are still relatively early in terrestrial operator networks.

Key takeaway: From a performance, capabilities, and SWaP perspective, both 4G/LTE and 5G/NR can meet or exceed the mobile broadband communications requirements for the Artemis scenarios discussed and envisioned through Artemis VII and likely beyond.

5.4 Core Network

5.4.1 4G Evolved Packet Core (EPC)

The Core Network is an essential part of the 3GPP-based network. Depending on the type of services and interoperability required, it includes different functions.

An example of the EPC architecture is described below, excluding the O&M interfaces.

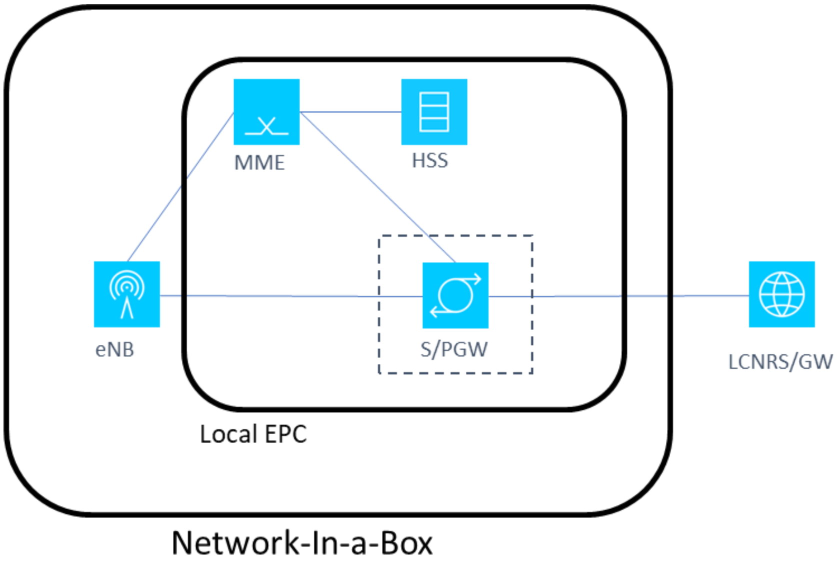

Figure 23 - EPC architecture example, excluding O&M

To be able to configure the EPC, e.g., provision and configure subscriptions, restart functionalities, etc., a dedicated custom Operation and Maintenance (O&M) interface and solution is needed. This has been presented below:

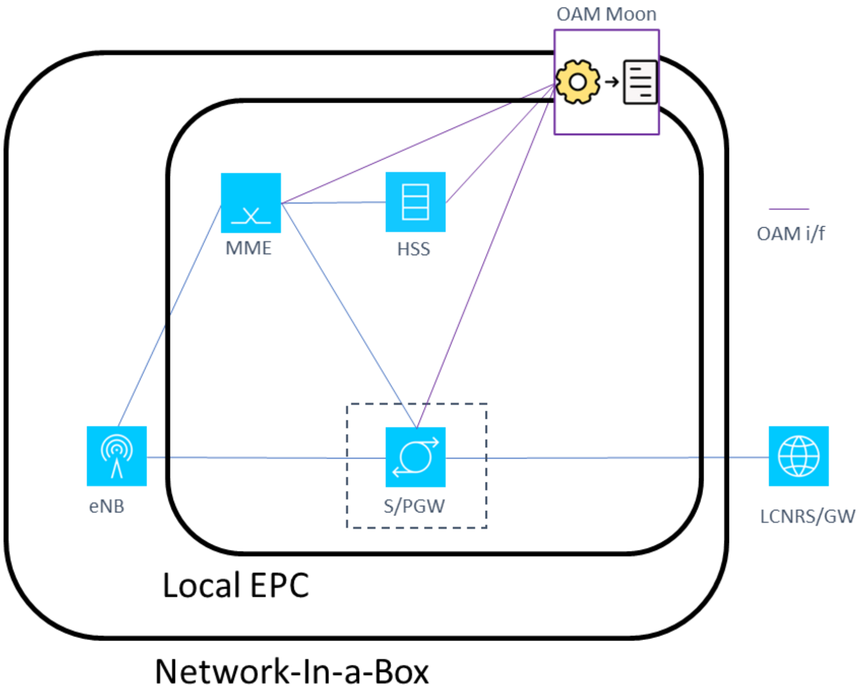

Figure 24 – 4G EPC architecture example, including O&M Moon agent

5.4.2 5G Core Network (5GC)

For the 3GPP Lunar surface network, an example of 5G Core (5GC) is shown below:

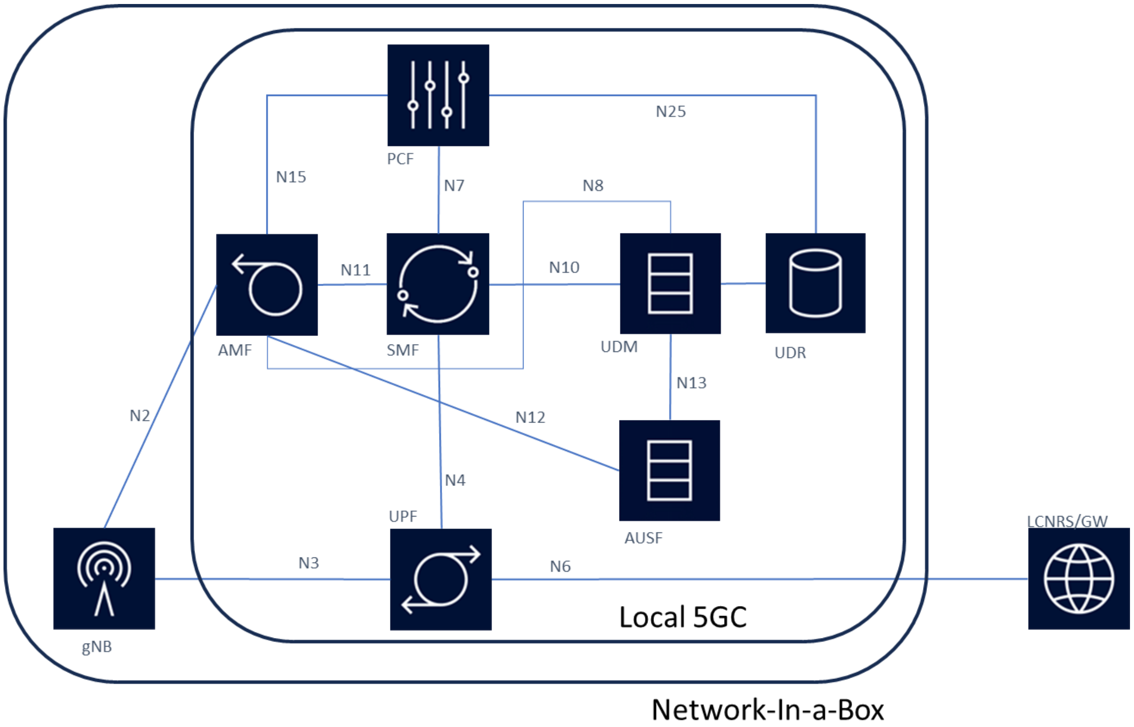

Figure 25 - 5GC architecture example

Below is the diagram or the proposed 5GC architecture, that includes the O&M service:

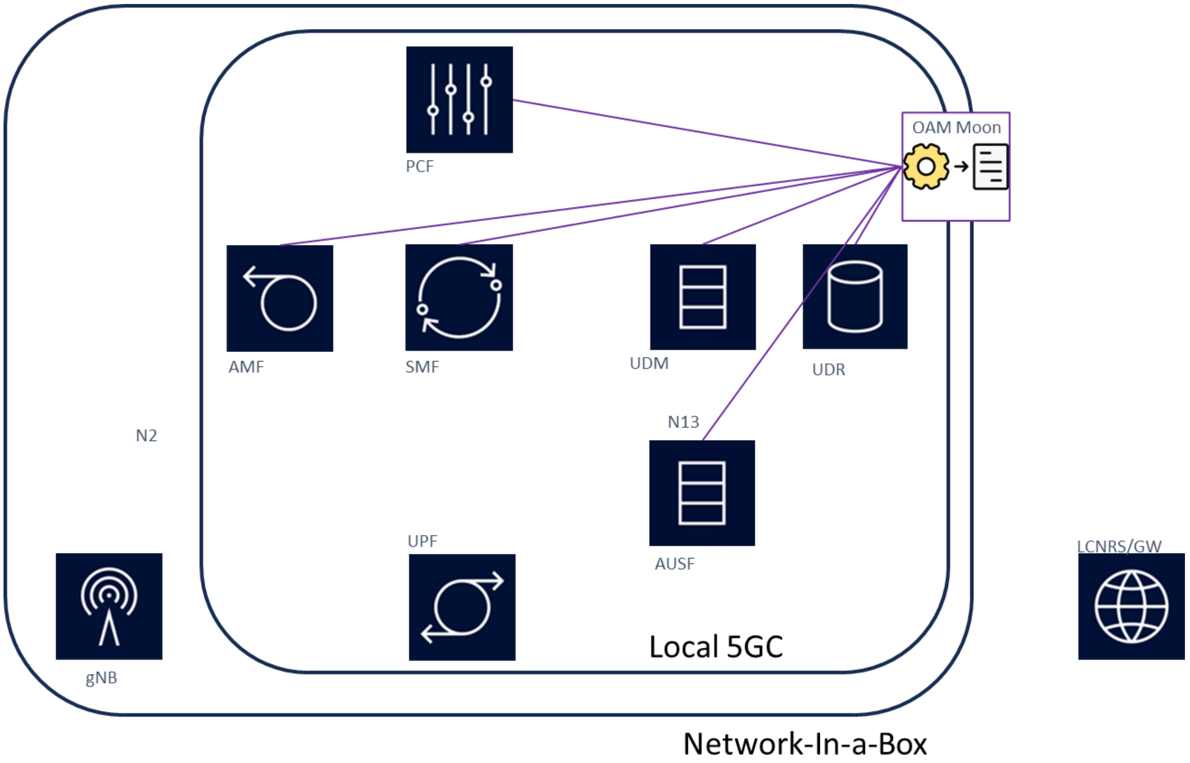

Figure 26 - 5GC architecture example, including O&M Moon agent

Part of the O&M Moon agent functionality needs to interface with 5GC Network Functions for proper provisioning, configuration and KPI monitoring.

5.5 Conclusions

In this section, several topics related to Radio Access Technology and Core Network have been presented and discussed. The key conclusions are:

- Both LTE and 5G NR can meet or exceed the mobile broadband communications requirements for the initial Lunar surface communication network.
- Both LTE and 5G NR can be implemented in an architecture appropriate for deployed Lunar surface communications.
- The LTE capacity can be increased by deploying more RF carrier(s) within each NIB, or by deploying multiple NIB(s). Proper network planning would be needed for future network expansion.
- 5G NR is more future proof for Lunar surface network expansion but:
    - Its scalability and performance benefits are not required in the Artemis scenarios explored.
    - The scalability and performance benefits may negatively impact SWaP.
- The following minimum standard releases are recommended: Rel.12 for LTE, Rel.15 for 5G and Rel.17 for 5G SideLink.

The final choice of LTE or 5G NR as a starting point needs to be made by weighing the pros and cons provided in this section against the other Artemis details and priorities of NASA. That said, Nokia recommends that, within the early to mid-2030's, NASA plan to utilize 5G regardless of its initial implementation's choice.

Further, Nokia recommends that NASA adopts a communication plan where the version of 3GPP used is no more than 1 1/2 – 2 generations behind the global 3GPP commercial plans.

5.6 References

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6 SW Application Engineering

6.1 Operations and Maintenance Architecture

6.1.1 Overview

This chapter provides an analysis of functionalities, challenges and proposed architecture of the Operation and Maintenance (O&M) service responsible for remote monitoring, management and troubleshooting of a Lunar Network communication system. The main objective is to indicate key areas that need to be addressed for this very specific use case of deploying a communication network in the lunar environment. However, the recommendations provided should not be treated as a complete set of requirements that the O&M service needs to realize as details need to be investigated during the detailed design phase.

6.1.2 O&M in terrestrial networks vs O&M for Lunar Network

The role of O&M layer is to monitor operation and manage telecommunications networks, both of which are essential components for ensuring their reliability and performance. Providing access to data and voice services is perceived as a critical service, thus a lot of effort is spent to make sure that telecom networks work in a reliable way and within the operational parameters they were planned for. Terrestrial network operators will always continuously monitor their systems for at least:

- Current operational state of the network elements and communication links between them,
- Any faults and alarms reported by the telecom equipment, indicating either service disruption, degradation or some unexpected state that needs to be analyzed and resolved,
- Current values, rapid changes or long-term trends in various level Key Performance Indicators (KPI) or performance counters. Each of these may indicate potential problems in network operation or change in how end customers use the system that may need to be addressed on the network planning or system configuration level,
- Security related metrics and potential incidents.

There are a few main differences between terrestrial carrier networks and the lunar system designed in this study from the O&M perspective.

The main differences are the scale of the network, the amount of data to be monitored, the number of network elements to be managed and the potentially constrained availability of the links to Earth. Operators of large terrestrial networks need to rely on aggregated monitoring and on some aggregated management actions. They cannot afford performing these operations with a high level of granularity. The initial deployment of a lunar system is a relatively small-scale operation where detailed monitoring would not only be possible but also desired. On the other hand, the lunar deployment has significant limitations on the bandwidth of the remote communication links (aka direct to earth or satellite relays) and this needs to be taken into account when designing this part of the system.

High reliability/availability of the network is a common requirement for both deployment environments, but only the lunar version has an extremely limited option for an on-site personnel access when critical problems occur. This means that some of the recovery scenarios, that while not desired but still possible in terrestrial environment, may not be viable in the lunar version of the system.

Another difference is the approach to the monitoring of individual UEs in the system. In large networks, detailed per device monitoring is only performed for debugging or legal reasons, and it can only be activated for a very small fraction of devices in the network. In the mission critical communication system covered by this study keeping the per-UE monitoring always active for all terminals active in the system would be the recommended approach.

Key takeaway: O&M should be specifically designed for the use case, provide detailed monitoring of KPIs for Core Network, RAN operation, with up to the base station level granularity and constant monitoring of current state of the UE devices and their critical parameters.

6.1.3 Minimum set of functionalities of O&M service for Lunar Network

Below list identifies the minimum set of user scenarios that the O&M service for the Lunar Network needs to provide.

- Real time monitoring of operation of network elements (eNB/gNB, Core, O&M agents), UE devices, and underlying virtualization platforms (if used),
- Handling of telecommands,
- Software upgrade of telecom protocol stack,
- Configuration change of Radio Access Network protocol stack,
- Configuration change of Core Network elements,
- Software upgrade / configuration change of any underlying Virtualization platform (if needed),
- Log collection and download.

6.1.4 Proposed O&M service architecture

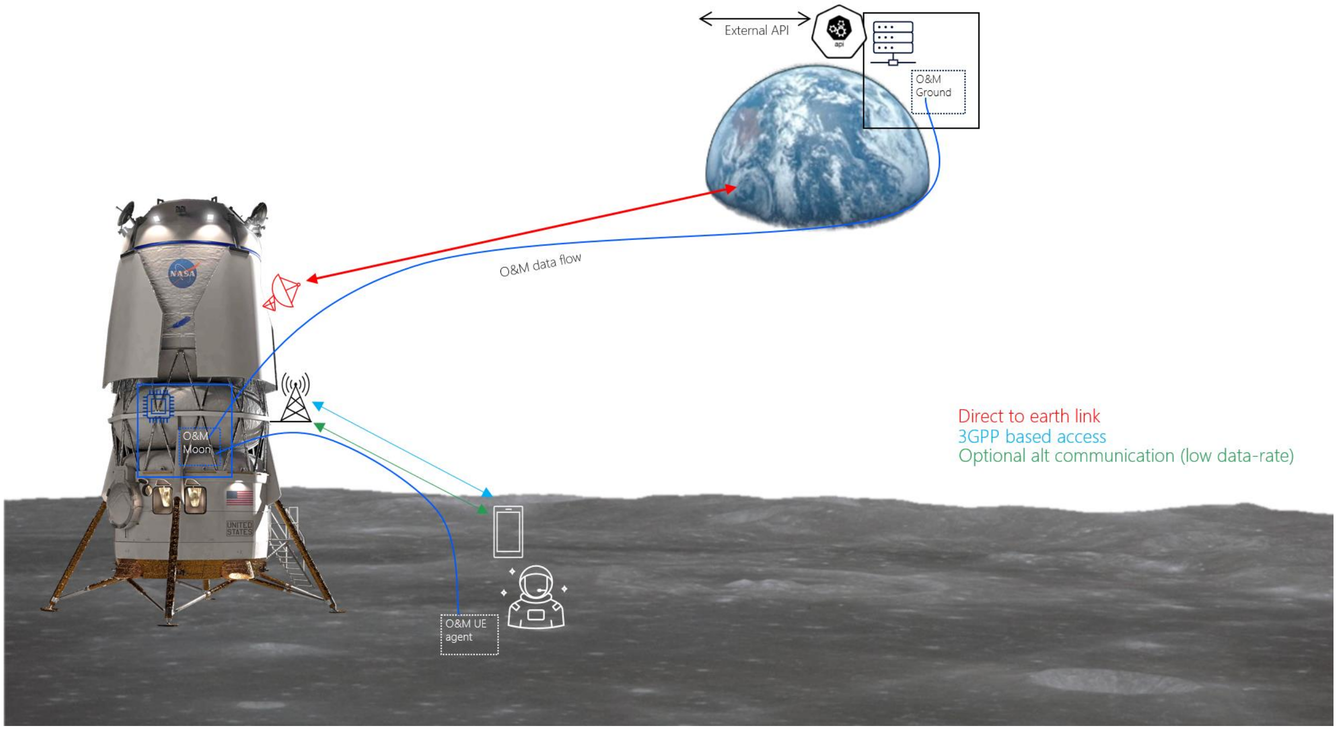
The proposed architecture for the Lunar Network O&M service consists of the following software-based components and communication links between them, assuring realization of the minimum set of functionalities required for remote management.

- O&M UE agent – this component provides monitoring and management of User Equipment devices.
- O&M Moon – responsible for data collection and management of lunar network Base Station (eNB/gNB) and Core Network functionalities.
- O&M Ground - termination point for management activities of Lunar Network and UE devices. This component terminates all communication links from the space segment of the O&M service and provides user interface and API for all data and management operations than can be performed on Lunar Network system.

Figure 27 depicts a high-level view of the O&M service architecture and location of each of the software components in the lunar system architecture. It specifically shows the architecture for the basic scenario with one NIB providing 3GPP based access near the HLS.

The diagrams also cover the scenario where an alternate means of communication is available for O&M traffic to reach the O&M UE agent (e.g. UHF or Wi-Fi based). This connection could potentially be used in troubleshooting and recovery scenarios involving failure of the UE device resulting in 3GPP connectivity loss.

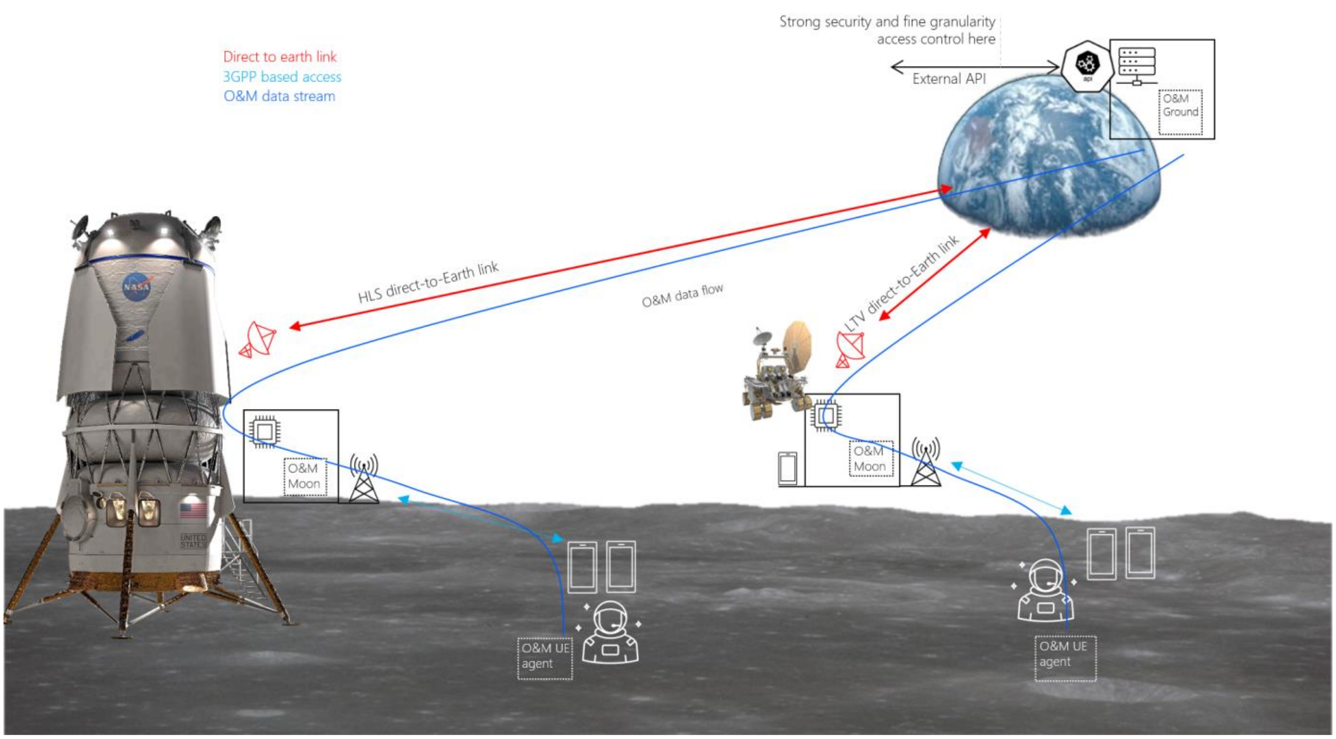
Figure 27: Basic architecture of O&M service for Lunar Network



However, the O&M service needs to also support more complex scenarios with multiple NIBs , with multiple communication links available and react to dynamic changes in the system topology, such as an additional base station being enabled or a direct-to-Earth links coming in or out of service. To address these scenarios, the O&M service will solely rely on the routing functionality of the lunar network system, keeping the functionality of each of the O&M service components isolated from the network topology changes as much as possible.

Figure 28 shows an example of O&M service components topology in a more advanced deployment scenario with 3GPP NIBs being deployed on HLS and LTV and two direct-to-Ground links available for communication between space and ground segment of the O&M service.

Figure 28: Extended architecture of O&M service for Lunar Network with both HLS and LTV deployed



The architecture diagrams presented here do not cover all possible deployment scenarios and are just illustrating the flexibility needed of the O&M space segment components.

Key takeaway: O&M service architecture consists of ground and space segment software components, located near or on the network elements that are managed. The architecture needs to be flexible and address multiple deployment scenarios with dynamic changes in communication links topology.

6.1.5 Monitoring and management considerations of User Equipment

In terrestrial telecom networks, the operator has no ability to take full control of the UE operation and many of the management actions are left to either the operating system, the software running on the device or the end user carrying the device. This approach is unbearable in lunar deployments, where any actions on the device need to be either fully automated or carried from the mission control center. Therefore, as opposed to the terrestrial scenarios, the O&M service of lunar telecom system should also provide monitoring and management services for User Equipment terminals. The proposed architecture of the O&M service presented in 6.1.4 covers that aspect introducing an O&M UE Agent component to the system.

6.1.6 Monitoring and management considerations of Radio Access Network and Core Network part of the system

Vendors of telecom equipment for terrestrial networks provide unified management solutions for their products i.e., network elements of the telecom system. Even though there are a lot of standardization efforts in this area, network management solutions often use proprietary protocols and interfaces for the management plane. Therefore, it is assumed that the O&M service should be an integral part of the lunar network solution and it is the responsibility of the vendor to identify best methods to obtain measurements and KPIs required for monitoring the system and provide means of configuring network elements it is built from.

One of the key assumptions when providing guidance towards the architecture and design of a lunar network system is to prioritize fault tolerance and system reliability vs configuration flexibility and extensibility. It is recommended that the actual system is designed and tested as an E2E solution.

6.1.7 Security aspects of O&M links and O&M service components

Various sources of security requirements have been identified as applicable for the management plane of the lunar communication system.

NASA-STD-1006A mandates FIPS 140 compliant protection for command links. All the functionalities of the O&M service are considered to be command links as they can be used to change the state of equipment used by a mission and impact critical voice and data comms. It should be noted that, if FIPS CMVP certification is needed for the system, it has significant impact on the schedule of initial system delivery and delays introducing changes to the system in future[4].

Other source of requirements for security aspects of O&M service are those for missions using Consultative Committee for Space Data Systems (CCSDS) procedures, and this study assumes that these procedures apply for the lunar network.

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[4] See Section 11 for details

6.1.8 O&M service protocol aspects

As indicated in paragraphs 6.1.4, 6.1.5, 6.1.6, the recommended approach for monitoring and management of lunar system is that the functionality gets included as part of E2E solution provided by the vendor delivering the system. From the mission control center point of view, all interactions should be performed through dedicated clients, or a set of APIs exposed by the O&M Ground component of the system. Therefore, many of the implementation decisions are left to the vendor and designers of the actual system. This specifically applies to the details of software interfaces between different components of the O&M service and how the communication between them is structured. This paragraph summarizes high level requirements that should be considered when designing that part of the system.

6.1.8.1 Efficient and scalable message serialization protocols

The main constraints for the interface between the O&M service components deployed on the lunar surface and on the ground are the high delay, limited bandwidth and possible reliability issues of the direct-to-Earth link used for communication. Therefore, the communication protocol on interfaces crossing the lunar to Earth boundary should be selected accordingly.

6.1.8.2 Protocol stack

It is assumed that IP based communication can be used on direct-to-Earth links as per CCSDS 702.1-B-1. With this approach there is the possibility to establish an IP based communication path between the O&M Ground, O&M Moon and O&M UE agent components. Different types of O&M traffic require mapping to different quality of service levels offered by the DTE links.

6.1.9 Time synchronization for network elements and O&M service components

This paragraph recognizes that operation and management of lunar network requires that each of the network elements and the O&M service components deployed on the Moon have access to an accurate time source. Having the clocks synchronized is required for proper operation of the system, timestamping telemetry data, timestamping any possible logs collected for troubleshooting purposes and proper management of security certificates. For more details on how the synchronization is achieved in the system please refer to Section 5.3.1 in RAN Access and Core chapter. It is also assumed that any disruptions to the upstream PNT service will not affect locally maintained time significantly enough to impact O&M service operation.

6.1.10 Conclusions

The study provides analysis and recommendations for the architecture of O&M service. The main conclusions are:

- The O&M service should be custom designed for the use case and take into account specific requirements of managing small scale telecom network providing critical services at remote and inaccessible location.
- High delay, limited data rates, potentially constrained availability and specific communication protocols on the links to Earth should all be factored in the architecture and operational framework for O&M service.
- All elements of the communication system (NIBs, UE, and O&M) need to be developed in conjunction with each other and cannot be developed in isolation of each other without the risk of significant issues or large integration efforts.
- Having the service designed and implemented with strong security features in place is also a mandatory requirement.

6.2 Voice Architecture

In this section, we describe the requirements, key technical challenges, and design recommendations for the voice application.

Even though the focus of this study is for the initial Artemis V mission, we understand that the number of Moon entities (e.g., astronauts, rovers) and their connectivity options will grow over time, we have elected to aim for a design that is general enough to scale with future Artemis missions. More specifically, the core of our design is motivated by the general case where the number of Moon entities (e.g., astronauts, rovers) and their connectivity options extend beyond those in the initial missions.

6.2.1 Voice Application Requirements

In this section, we lay out the high-level voice application requirements. We separate them into five categories: data path, control path, implementation, non-functional, and miscellaneous.

6.2.1.1 Audio Data

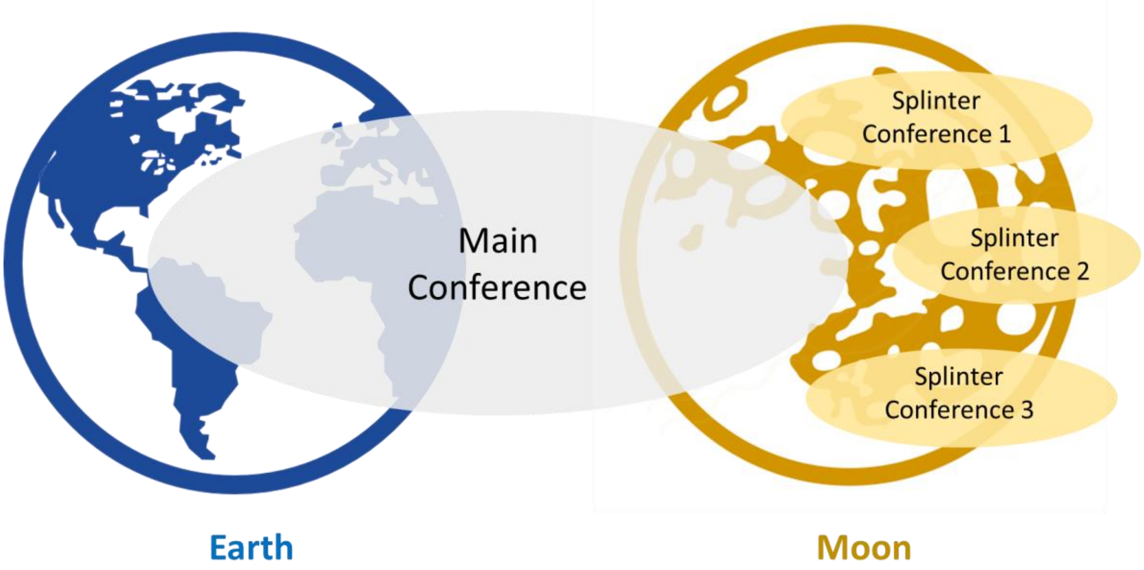


Figure 29: Main and Splinter Conferences

The basic service model of the voice application is a single always-on conference call. The single conference call connects participants on Earth and on Moon. The constant-on nature means there is no need for the Moon participants to set up or join the call; the conference is on as soon as the mission starts. The number of Moon participants is small (in 10s) and fixed on a mission basis (excluding failures). The number of Earth participants can on the other hand be large and dynamic.

The default is that all participants are on a single call. However, potential communication failure may prevent a participant from reaching the single call. For the Moon participants in particular, because of mission activities, it is critical they maintain voice contact with as many other participants as possible. To capture this requirement, we define two terms:

- Main conference – this refers to the single call conference that connects the reachable Earth and Moon participants.
- Splinter conference – this refers to a conference that connects a subset of Moon participants and is disconnected from the Main conference. Such splinter conferences should be ephemeral in nature, they come and go as network connectivity changes.

At any time, there is at most one main conference, but there can be multiple disconnected splinter conferences. The voice application should try to maximize the number of participants connected in the Main conference, while minimizing the number of splinter conferences. From a voice experience perspective, as splinter conferences got detached and re-attach to the Main conference, the transition should be seamless without disruption.

Lastly, the primary audio data focus is speech. In other words, when there are conflicting design choices, the voice application is optimized for speech delivery, rather than general fullband/wideband audio.

6.2.1.2 Voice Control

Similar to a business conference call, we anticipate certain voice control features to be desirable in a mission-oriented voice application.

The two most important conference level voice control features are the ability to: (1) mute/unmute a participant; and (2) add/drop a participant.

Due to the sensitive nature of these actions, access control (e.g., host) may be required; and even then, the action may not apply to all participants. For example, it may never be possible or desirable to add/drop a Moon participant.

Apart from the conference level control, local voice control may be available to individual participants. For example, a participant may be able to mute/unmute itself. However, a Moon participant may not be able to add/drop itself.

6.2.1.3 Implementation

The voice application should be able to support multiple audio codecs. There is a minimal set of codecs that is supported.

The Moon participants are typically energy constrained; thus, the implementation should be energy aware, and may support adaptive behavior based on energy consumption/remaining power.

6.2.1.4 Non-functional

As mentioned before, the conference should be highly available. There should be minimal downtime. Typically, voice availability requirements are specified in nines. For example, five nines mean 99.999% availability, which translates to less than 6 minutes of downtime per year. But given that missions are discrete one-time events, such specification is not too meaningful. Instead, high availability means the requirement to do application monitoring and automatic restart.

Another non-functional concern is security. All data path and control path should be secured such that unauthorized intrusion into the conference is not possible.

6.2.1.5 Miscellaneous

Due to the distributed nature of the voice applications, each participant has only a local "view" of the entire conference. In particular, some of its own audio may not reach everyone, and it may not receive the audio of all others.

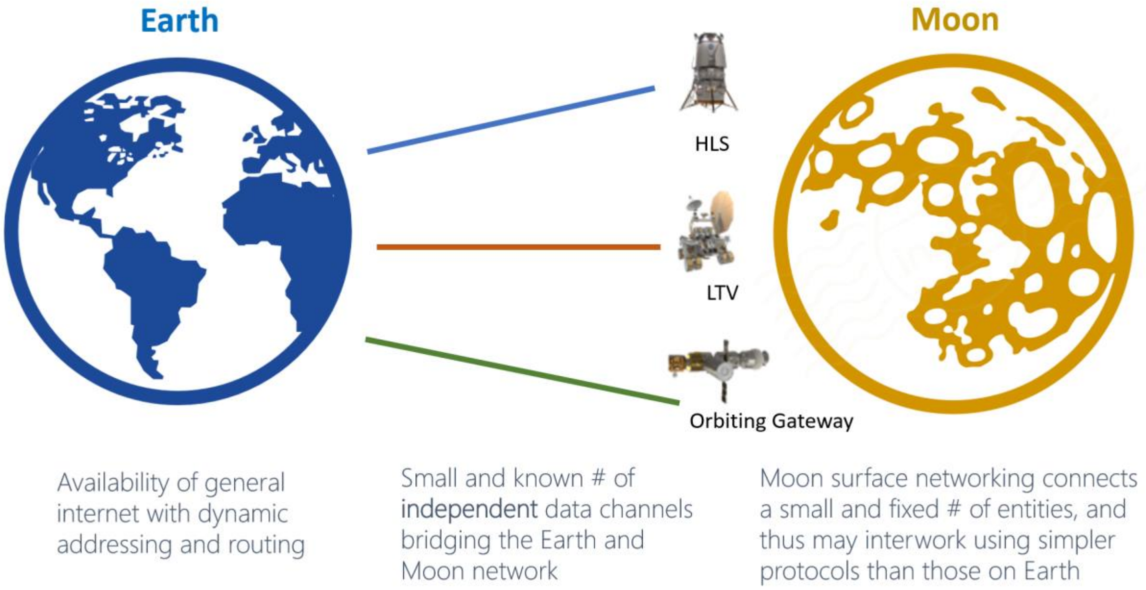
As a result, it may be useful for each participant to maintain a local archive of its local view of the entire conference. This local archive records all audio data that was sent and received by the participant. The main purpose of this archive is not for local review, but rather for post-mission auditing. Local storage is needed to support this feature.

Lastly, there may be interoperability requirements with existing conference capabilities already deployed within NASA.

6.2.2 Networking Considerations

The voice application runs on top of an underlying networking layer that extends from the Earth to the Moon. We highlight a few considerations on the networking layer that can help better understand the voice application design.

6.2.2.1 Earth vs Moon Networking



Availability of general internet with dynamic addressing and routing

Small and known # of independent data channels bridging the Earth and Moon network

Moon surface networking connects a small and fixed # of entities, and thus may interwork using simpler protocols than those on Earth

Figure 30: Earth vs Moon Networking

At a high level, the network is made up of 3 components:

- Earth network – this would be a network constructed using general internet technologies that support fully dynamic addressing and routing.
- Earth-Moon links – there are a small and known number of data links connecting the Earth network and the Moon surface network. These links are constructed using different technologies and can be understood abstractly as independent point-to-point links.
- Moon surface network – The Moon surface network is dynamically configured using the networking capabilities of the various Moon-based entities. There can be multiple networks that dynamically interconnect with each other based on the relative mobility of the different entities.

The configuration/internetworking of the Moon network can be automatically managed using some internetworking layers operating within the Moon entities. This internetworking layer ensures maximal connectivity of Moon entities to the Earth-Moon network. Any disconnected networks would be connected to the main Earth-Moon network as soon as the connectivity can be established.

6.2.2.2 Voice Transport

With multiple networks involved, native end-to-end voice is not possible. Instead, voice is transported as packets and routed through the networks to their destinations. A key measure of the final voice quality is the quality of the network paths, or more specifically, the amount of packet losses suffered as the packet traverses the multiple networks.

Some key factors that contribute to packet losses are signal quality, networking issues and congestion.

6.2.2.3 Conference Partitioning

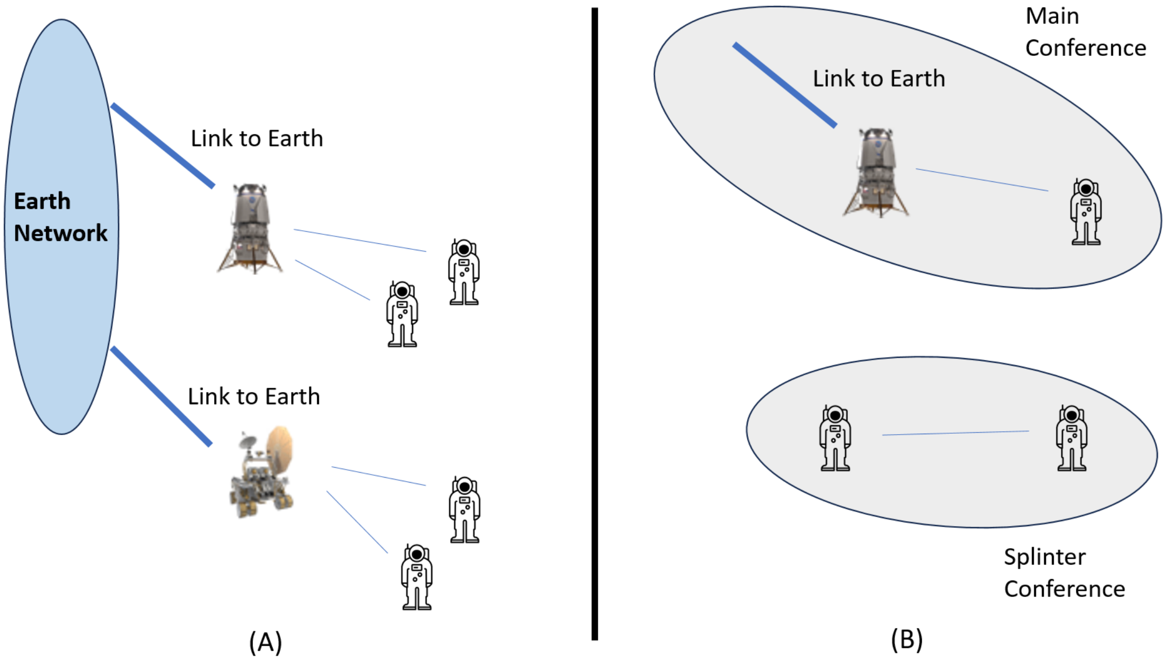


Figure 31: Main vs Splinter Conference

The Moon network can experience network partitioning. In general, a Moon network partitioning may or may not lead to a conference partitioning.

Consider Figure 31. In (A), there are two Moon networks that are not connected to each other via other Moon networks but can still reach each other via the Earth network. In this case, there is still a single main conference, and there is no conference partitioning. Even though the top and bottom astronauts can talk/hear each other, there will be significant delay in their voice communication.

In (B) however, the top network is connected to Earth while the bottom network is a standalone network on its own. In this case, the astronauts in the top network are joined into the main conference; while the astronauts in the bottom network are joined into a separate splinter conference. When one of the bottom astronauts get within the range of the HLS, connectivity will be established between the top and bottom networks. This will re-attach the splinter conference and join the two bottom astronauts into the main conference.

6.2.3 Voice Conferencing Architecture Approaches

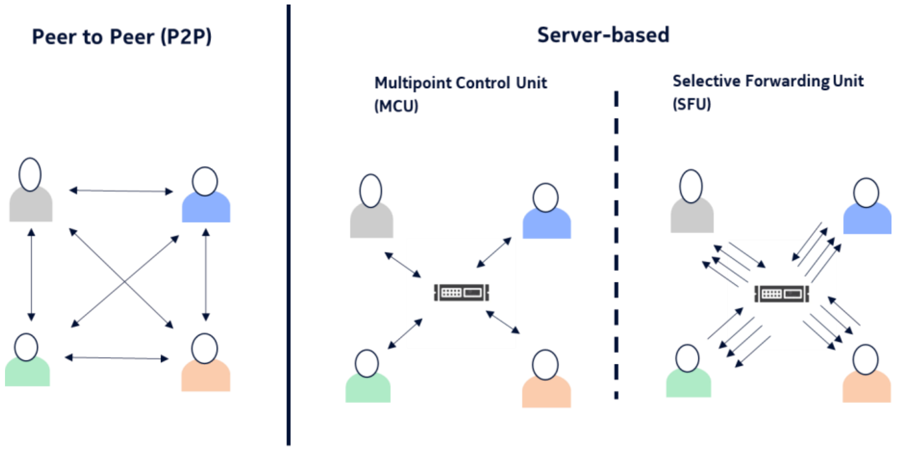


Figure 32: Voice Conferencing Architecture

There are 2 main architectural approaches to designing voice conferencing applications, depending on whether a central server is used:

- Without a central server: Another name for this approach is Peer to Peer (P2P). Without a central server, each participant is aware of all other participants and will communicate directly with all other participants, creating a fully connected communication mesh. Not having a central server means one less component to operate; in return, the processing/communication load at each participant will now scale with the size of the conference. For constrained end device, this will not work well with large conferences.
- With a central server: The use of a server means an extra component must be instantiated and operated; in return it eases several operational and scalability issues. For example, both conference membership management and voice data forwarding can be offloaded to the server, lessening the processing/communication requirements of each participant.

6.2.4 Key Design Challenges

There are several key challenges that need to be addressed in the design of the voice application. To list a few:

- Moon interworking dynamics: e.g., impact of underlying network changes on the voice application
- Network performance variations: e.g., impact of bandwidth, packet losses, latency, etc.
- Human voice experience handling
- High-availability design
- Power consumption

6.2.5 Conclusions

Compared to a typical business conference, the Artemis voice application has a few distinguishing and challenging requirements:

- The need to maintain local voice conferencing for Moon participants during disconnection from the main conference is unique. In order to provide a seamless voice experience, the key challenge is to ensure fast network convergence, followed by fast application convergence.

- The Earth-Moon link presents two significant challenges. First, its availability and loss profile is highly dissimilar to a typical Earth or Moon surface link. Second, it has a disproportionally large latency that makes interactive voice difficult.

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6.3 Video Architecture

6.3.1 Introduction

Digital video has evolved greatly since the 1990's with the development of several supporting technologies. Networked video conferencing has become the norm in recent years. Mobile video entertainment and communications is now common. Video touches our everyday lives and is expected. Video delivery has always had its challenges and dominates the bandwidth consumed on the different networks. Its growth has been increasing from increased viewing of video content [1]. The challenges of transmitting video in a space environment is even greater. In this section, we make the following key recommendations regarding end-to-end video transmission from Lunar Missions:

- Realtime video will transit LunaNet over Direct-to-Earth Links (DTE) and leverage the networking solutions implemented for digital voice communications.
- The LunaNet interfaces are ideal control points video services utilizing the Delay-Tolerant-Network (DTN) aspects of LunaNet.
- The video bitstream syntax can be constrained to help maintain the quality through transmission and to mitigate error effects.
- H.264 is still a viable video codec except at lower bitrates where H.265 performs much better.

6.3.2 Requirements

Encoded video streams were described as follows:

- 1080p (FHD) or 4k streams at 30fps using H.265 with data-rate of 3-12 Mbps/each.
- An EVA team with at least four cameras aggregate.
- One LTV per mission with at least two cameras and two hosted crew members.

To meet these needs, we have recommendations in specific areas for the delivery of Lunar video. In summary, these recommendations fall in the categories of Networking, Codecs, and Bitstream Syntax.

6.3.2.1 Networking

The network picture between earth and Moon is complex now and is expected to remain that way in the future with the availability of multiple technologies and potentially vastly different capabilities. A simplifying assumption is that the confluence of these different communications links is for the 3GPP network to bridge/interface into LunaNet [2], [3]. From the standpoint of video routing and networking, video streams will leverage the solutions necessary to support voice. Further, given the nature of the environment, the transport and error management must be considered carefully.

6.3.2.2 Codecs

While H.265 [4] appears mandated by NASA, it is only currently gaining wider acceptance. H.264 [5] should not be ignored as the benefit of H.265 is primarily at the lower bandwidths. Over the next decade, we can expect that the next generation of codecs (e.g. H.266 [6]) will also be gaining acceptance.

6.3.2.3 Bitstream Syntax

Many video codecs are black boxes with limited control. Constraints can affect transport, error resilience, and the over quality of the video stream. The structure of the video stream as set at the encoder will affect the overall transmission and quality.

6.3.3 Video networking

Off world networking provides unique challenges. These are the ultimate in long delay networks as compared to terrestrial networks where delays more than 100ms are considered long! For lunar communication, propagation to the Moon adds another 1.25s each way with any additional relays.

To address the needs for data communication to the Moon and beyond, NASA has been working on the LunaNet project [8]. This network provides interfaces for Direct-to-Earth (DTE) as well as Delay-Tolerant-Network (DTN) services. The DTE links is the obvious choice for real-time video and data whereas the DTN links are suited for batch file-oriented transfers. While LunaNet appears to be a network black box, it provides basic IP link layer and network layer connectivity for user applications as shown in Figure 33 [3] These are based on CCSDS standards such as [9], [10].

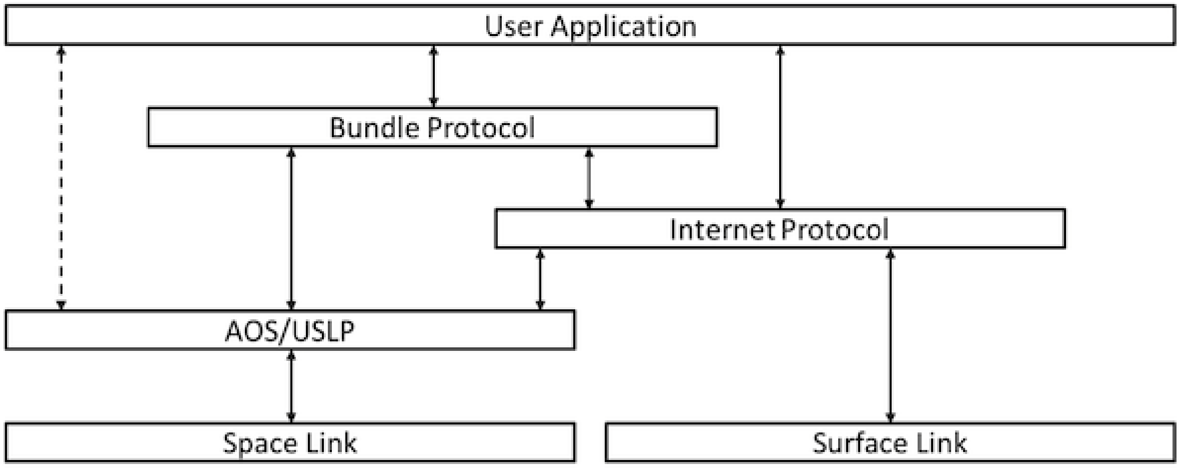

Figure 33: LunaNet Simplified Protocol Stack

For real-time video communications, error-free transmission is not necessarily mandatory if it causes excessive latency. In fact, retransmission of error data may needlessly cause delays and a congestion collapse.[11], [12] Losses can result from tail drop (overflow) of transmission FIFOs which is the worst data to discard. To remedy these effects, we recommend avoiding use of TCP on long delay networks and to ensure that the network layers support Active Queue Management (AQM) schemes such as CoDel[13] or CAKE[14] which have support in many Linux kernels.

One observation is that within a LunaNet network, multiple pathways exist with dynamic network reconfiguration depending on the availability of different physical links and rates. This is further complicated by the various reconfiguration scenarios anticipated by the voice segment. To address this, any network node that can reconfigure realistically needs to constantly monitor possible links to make a local determination of which network route to utilize.

The rationale is that links must be rerouted prior to failure of active link. With the possibility of redundant hardware, the existence of multiple radios enables the possibility of being able to actively monitor alternate links, however, this comes at the expense of addition power and reliability of redundant components.

The presumption is that LunaNet will take care of the reroute function to Earth and to the Lunar Gateway Satellite. For the purposes of the Astronaut's suit, as it is not a LunaNet terminal, it must intelligently monitor and reroute as necessary to support operations.

6.3.4 Video server functionality

One aspect of LunaNet is particularly useful to supporting Lunar missions. While the focus has been on real-time video that would be transmitted to earth via DTE connections, the Bundle Protocol and DTN features are ideal for video services. Video transiting and entering the LunaNet will bridge into the DTE links and will be re-encapsulated as needed. Simultaneously, video streams can be archived into a video server node. This is largely a data formatting operation as opposed to processing which is not processing or power intensive. Deploying a video server at a LunaNet interface could offer the following benefits/capabilities:

- Video that is not transmitted to Earth can be downlinked opportunistically when bandwidth is available.
- In time of high errors, on demand replays become feasible.
- Bulk video archives can be archived to physical media for a return-to-Earth flight.
- On demand transcoding could be made available at lower resolutions or lower bitrates to preserve bandwidth while preserving high resolution video for future analysis.
- The nature of the store-and-forward aspect of DTN would allow aggregation away from a mobile platform of an LTV toward a primary server perhaps on the HLS or gateway satellite.

The above list is just a few features of a LunaNet video server. The point of significance is that this is the ideal junction that allows for a lot of features and functionality to support lunar missions.

6.3.5 Bitstream syntax

Video encoders have a different philosophy than voice encoders. Compliance to a video standard is essentially conformance to a bitstream syntax (and profile) without a quality bound. The decoder must not only decode any valid bitstream but must also behave well even for malformed bitstreams and in the presence of errors.

The encoder implements a tradeoff between computational complexity and bitstream efficiency. The intellectual property in the encoder includes the heuristics behind forming the bitstream. In rough terms, successive generations of encoders over the last 25 years have each gained 2x bandwidth performance at the expense of 4-6x computational requirements [18], [19] which should have an influence on power.

Some cameras may have the encoding functionality embedded with the sensor. In these situations, encoding parameters might not be exposed. Regardless of the location of the encoder, the structuring of bitstream can affect the transmission and overall end-to-end quality.

6.3.5.1 Video encoder

Video encoding technology has been incrementally improving over the past 30+ years with the advent of semiconductor technologies. Currently H.264 is in widespread use and H.265 is gaining market acceptance as codecs become more available. H.265 offers a roughly 2x improvement in bandwidth for a 4x increase in computational complexity.

6.3.5.2 Bitstream Structure

Bitstreams are characterized by high-quality encoded images that rely upon spatial redundancy like a still image. These pictures based on Intra-frame (I-frame) are known as I-frames, I-pictures, or anchor frames, and they stand on their own. The real bandwidth compression results from exploiting temporal redundancy or motion that occurs between images in a sequence. In a first case, predictive pictures are encoded based on the previous encoded image. These are known as P-pictures. Figure 34 is a Group-of-Picture (GOP) example showing the dependency of P pictures upon previous pictures.

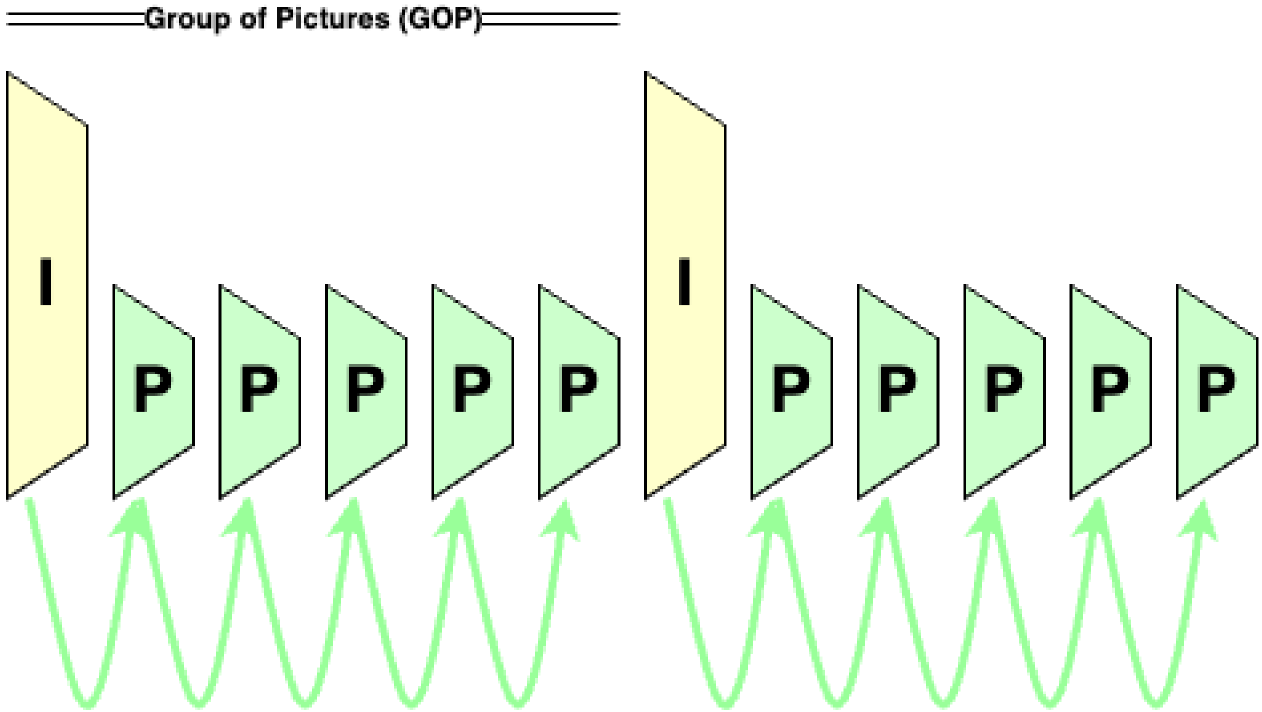

Figure 34: Group-of-Picture Example

Another type of image is used based on bi-directional prediction known as B-pictures. In this case prediction is based not only on the previous encoded image, but a future image. B-pictures potentially increase prediction accuracy and codec performance at the expense of computational complexity, memory, and latency since the encoder must buffer the "future" pictures and operate several images late.

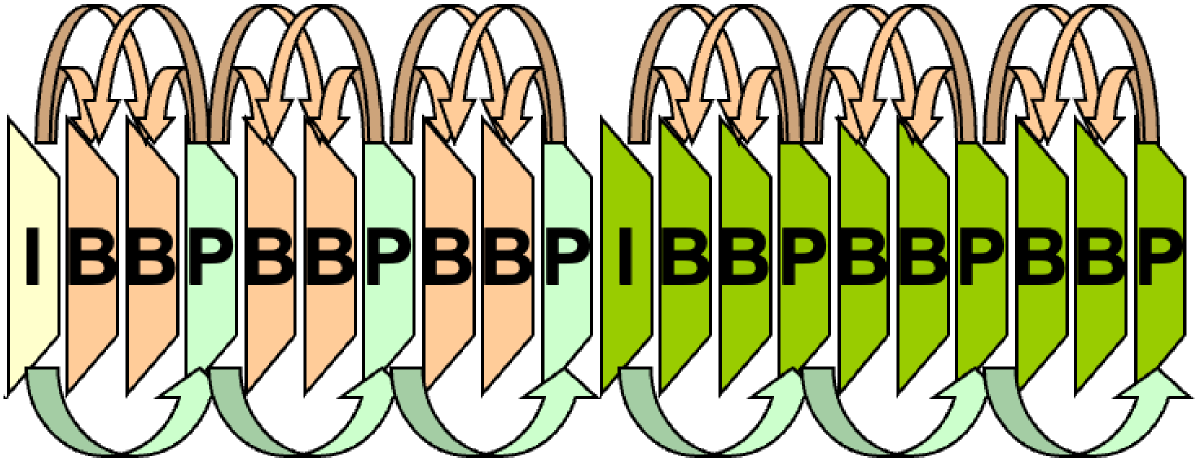

Figure 35: IBP Sequence Example

A sequence of pictures is known as a Group-of-Pictures or GOP. An important characteristic of image sequences is the distance between the I-frames which is known as the GOP size. The reason why this is important relates to the actual communication and resilience.

6.3.5.3 Bitstream transport

The structure of a video bitstream also influences its transport. A practical issue that results is that periodically a block of data is presented to the network for transmission.

6.3.5.4 Codecs

Recently, several hardware codecs have become available on the market. Even though there are software solutions such as FFmpeg [22], special purpose products exist that have custom purpose hardware accelerators surrounded by a flexible core. Programmable FPGA hardware such as some Xilinx Zynq UltraScale devices include CPU cores and a custom video encoder.[23] Embedded systems now often have multiple CPU cores with custom video acceleration hardware as found in the Nvidia Jetson family.[24] It is also noted that some of these devices have had some level of radiation testing reported in the literature such as [25]–[28].

6.3.6 Conclusions

- Realtime video will transit LunaNet over Direct-to-Earth Links (DTE) and leverage the networking solutions implemented for digital voice communications.
- The LunaNet interfaces are ideal control points for video services utilizing the Delay-Tolerant-Network (DTN) aspects of LunaNet.
- The video bitstream syntax can be constrained to help maintain the quality through transmission and to mitigate error effects.
- H.264 is still a viable video codec except at lower bitrates where H.265 performs much better.

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7 Hardware Engineering

7.1 NIB Hardware Engineering

7.1.1 Network in a Box (NIB): Definition and requirements for component selections

For lunar deployments, the use cases defined for a communication system are different from the ones for typical terrestrial deployments. The network implementation is therefore expected to be somewhat different down to the HW architecture of the network elements.

Typical requirements for a terrestrial network are:

- Multiple cells for coverage of a sizable geographical area.
- Extremely high throughput for large number of concurrent users.
- Cost optimized.
- Upgradeable.

A lunar implementation, especially in the first phases of exploration, on the other hand, has different use cases (a limited number of simultaneous users with high throughput, limited geographical coverage compared to a terrestrial cellular network) and a requirement to optimize the network equipment for size, weight, and power.

Current terrestrial networks are typically consisting of:

- Servers (using general purpose processors [GPP] such as x86-64 based CPU's).
- Custom HW boards (typically for the lower layers such as L2/L1 and Radio).
- CPU (x86/ARM), ASICs/SoCs (custom design), FPGA.
- Radio components (amplifiers, etc.).

These building parts are usually distributed in different network elements, that can be in proximity or far from each other. Usually, the size and the complexity of each piece of equipment is dictated by the use cases typically requiring support for several hundred simultaneous users and extremely high throughput.

A good approach for a lunar network is to adapt the equipment size according to the most demanding use case requirements and then integrate a full network in a single enclosure, as proposed in Section 4.2.1 and being used in the LTE Tipping Point demonstration [1]. Such an enclosure would contain the radios, baseband (L1 and above) and core network, see Figure 2 for an expanded, more detailed version of what was presented in the E2E system architecture section.

A compact design would reduce SWaP (Size Weight and Power) and environmental support function requirements (like cooling, power distribution, mounting, interconnections, etc.).

Environmental constraints are going to dictate the design of any hardware that is used in lunar environment. To name a few:

- Reliability requirements (see Reliability Section 8.2 for further details), especially for crewed missions.
- Mechanical (Shock, Vibration, Acceleration, …) for surviving launch, transit, landing on the Moon.
- Thermal Design for operating in lunar harsh environment.
- Radiation tolerance, to survive and properly function in the lunar environment.

These requirements are to some extent codified in several standards, which are described in the Reliability section. Space grade components need to be qualified according to these standards or obtain a well justified waiver.

Radiation tolerance seems to be the most difficult requirement to fulfill, especially for highly integrated and complex systems such as System on Chip (SoC) and System in Package (SiP).

SoC's and SiP's are used in the industry to "pack" several complex functions and reduce SWaP by integrating different technologies onto the same component or package. These are usually custom components with several proprietary IPs. Qualification of these components for radiation and other requirements would be the preferred solution whenever possible since suitable space grade alternatives are not always available.

For example, radiation tolerant versions of 3GPP SoC/SiPs do not exist to date, and would require deep IC re-design, using both more resilient processes (like SOI) and/or ah-hoc mitigation techniques (like Error Detection and Correction, memory scrubbing, triple redundancy).

One alternative to full re-design is to use radiation tolerant programmable firmware (FPGA) qualified for space applications. Some of these components are in fact available, with different sizes, complexity and "hard-IPs" built-in.

FPGAs can be used to substitute some of the digital electronics, especially for those functions requiring HW acceleration (for example wherever DSP processors are used.)

Another important component to consider would be the mixed signal (analog and digital) section of the radio. In commercial terrestrial networks, this radio section is usually a very compact integrated circuit (RFIC), containing all the Analog to Digital and Digital to Analog converters (ADC/DAC), plus all the related logic necessary to perform the functionalities of the Digital Front End.

The computational engines for the remainder blocks of the NIB (for L2 and above, plus core network) can be implemented using more traditional solutions such as general-purpose processors (GPP) like x86 processors, ARM processors, etc.

7.1.2 Size, Weight, and Power considerations

Size Weight and Power (SWaP) has a fundamental importance in Lunar Communication systems for driving costs of deployment and operation.

In fact, power is a scarce resource in the lunar environment, and transportation costs are directly tied to the mass of the equipment. Therefore, minimizing SWaP is fundamental for the mission operational and economic viability.

As outlined in Section 7.1.1, radiation tolerant digital components are in general more "power hungry" than COTS equivalents; therefore, in general radiation tolerance has an impact on SWaP. One can estimate the impact by comparing similar designs and estimating the different power consumptions.

In general, it can be concluded that moving from a commercial optimized SoC component to a Rad-Hard solution significantly increases power consumption.

This power consumption increase translates in power dissipation increase of a similar amount, which in turns impacts the mass / weight of the overall solution.

If the NIB is integrated on a partner thermal subsystem, it would "pass on" increased dissipation requirements to the partner's thermal management system.

The physical size of the PCBA should not be significantly impacted by using radiation tolerant components; however, a size increase might come as a consequence of using IPC Class 3 PCB design principles, which includes certain design rules affecting PCBA size.

7.1.3 Conclusions

- The proposed NIB architecture is a SWaP-optimized concept for lunar deployment, resulting in reduced size and optimized power consumption. A NIB architecture can be derived leveraging existing terrestrial building blocks both for 4G and 5G.
- The extra HW reliability requirements typical of space applications (especially radiation tolerance) prevents the use of certain components that are commonly used in terrestrial networks. Suitable space grade components need to be selected for substituting the non-compliant ones.
- It needs to be noted that moving to space grade components implies a power consumption / dissipation increase which may result in size/mass increase too, negatively affecting SWaP.

- It would be strongly recommended to characterize some of COTS components, especially custom SoCs, to evaluate their current performance and their ability to meet the reliability requirements.
- A hybrid approach of using a mix of COTS and space grade parts can potentially have a positive impact on SWaP and development costs.

7.2 UE Hardware Engineering

7.2.1 Key 3GPP UE Components

The following sections describe the key components of a 3GPP UE solution.

7.2.1.1 Micro-Controller Unit (MCU)

There are two main alternatives for MCU selection depending on the selected mobile platform architecture.

1) If the mobile platform architecture is based on a handset-targeted platform, it is natural to use the MCU system delivered as a part of that platform.
2) If the mobile platform architecture is based on cellular modem modules, the approach would be to use a separate MCU system.

7.2.1.2 Memory, RAM, and Flash

Memory components need to be carefully selected for radiation tolerance. Some interface incompatibilities (e.g., LPDDR vs DDR) need to be considered carefully during design phase. In the highly integrated handset architecture, RAM is often integrated to the MCU using PoP (Package on a Package). Selecting the right memory component is fundamental to achieve the required performance targets.

7.2.1.3 Other components and considerations

Other components or integrated devices such as cameras or audio must be supported with the selected MCU and integration and testing are therefore critical. The evaluation of commonly used camera and audio busses on the EVA suit architecture is also recommended to be carried out during early design phases.

7.2.1.4 Cellular Modem

A cellular modem is a highly integrated and complex system that can run all required cellular functions (e.g., baseband, RF, multi-RAT (2G/3G/4G/5G), multi-frequency) in a very power-efficient manner. Cellular modem companies spend billions of dollars in R&D every-year and employ tens of thousands of people on designing, developing, and testing such solutions. And every year new functionalities are developed and deployed keeping the solutions on par with 3GPP standards development (as can be claimed for the counterpart 3GPP NIB).

Given the complexity and integration level of UE modem’s SoCs and the significant annual R&D investment and expertise needed, it is unrealistic to build a cellular modem from scratch based on space graded / rad-hardened FPGAs and expect a similar level of performance, interoperability, SWaP, or the feature rich capability set of a commercial cellular modem SoC. Additionally, establishing and maintaining 3GPP compliance and interoperability would be a huge challenge as the commercial modem companies invest a significant amount of resources to ensure 3GPP compliance and interoperability every year.

Using a commercial modem SoC is the recommended path forward. That said, we also recommend that a detailed characterization of their performance and tolerances be started as soon as possible. This characterization is critical to understand the limitations of the commercial modems for further consideration and required mitigations in the design phase.

7.2.2 Device to Device (D2D) Communications

One of the most critical requirements is the ability of the astronauts to communicate to each other, even if the 3GPP Network is not available. This requirement leads to the need of Device-to-Device (D2D) communication capabilities. There are multiple ways to implement the functionality, e.g., SideLink, C-V2X, or Wi-Fi based solutions. It is also fundamental to guarantee seamlessly switching between network-based and D2D communications.

7.2.2.1 3GPP SideLink

3GPP introduced SideLink specifications in Rel. 16 (in support of 5G NR) with expanded capabilities in Rel.17 and Rel.18. It offers a communication solution with access control, voice, and data in both network-connected and device-to-device scenarios, automatic path control and priority schemes to guarantee service in high priority use cases, relay functionalities, etc.

Pros:

- Native support of audio and video.
- Seamless integration and operation with network-based communication mode.
- Integration on cellular modems for optimized SWaP.
- Both D2D and Relay functions are supported.
- Prototype availability for testing and development.

Cons:

- Committed support in commercial cellular modem releases is not firm but positive outlook is expected based on conversations with a leading cellular modem manufacturer.

7.2.2.2 3GPP C-V2X

C-V2X is a communication system designed for the automotive industry. It targets sensor data delivery by broadcasting it to devices in proximity. The communication API is targeted to well-defined automotive use cases which make it challenging to use in our use cases.

Pros:

- Data rates are high (in new revisions).
- Demand of high reliability coming from automotive industry.
- Wide user group leads to best test coverage (if feature is used the same way as in the planned device)

Cons:

- APIs are tailored for automotive use cases.
- Audio implementation using c-V2X is not a core requirement for automotive industry.
- C-V2X operates in what is known as the ITS band in 5.9 GHz spectrum.

7.2.2.3 D2D Recommendation

Our recommendation is to consider 3GPP SideLink as the D2D technology based on its described benefits and the ability to tightly integrate it with the network-based communication mode. Further, we recommend establishing demonstrations and testing of the technology as early as possible.

Existing UHF solutions in EVA suits are recommended to be maintained in the first Artemis missions to provide back-up communications links.

7.2.3 Conclusions

Different approaches can be followed for designing a 3GPP UE solution for Artemis V. We recommend the use of a commercial modem SoC as a fundamental building block of the 3GPP UE. That said, we also recommend that a detailed characterization of their performance and tolerances be started as soon as possible. This characterization is critical to understand the limitations of the commercial modems for further consideration and required mitigations in the design phase.

In terms of D2D communications, it is recommended that 5G SideLink be considered as the technology for astronaut-to-astronaut communications given its benefits, functionality/capability set and ability to operate side-by-side with the network-based communication mode. Existing UHF solutions in EVA suits are recommended to be maintained in the first Artemis missions to provide a back-up communications links.

While 5G SideLink support in commercial cellular modems is not formalized at the moment, discussions with a leading manufacturer in the U.S. present a promising outlook for both prototype availability and future functionality support in commercial modems. We recommend establishing demonstrations and testing of the technology as early as possible to evaluate its current state.

7.3 RF Antenna Engineering

7.3.1 Directive, High Gain NIB antennas

7.3.1.1 Dipole antenna

A simple, widely used antenna type is a dipole. Using a reflector, the beamwidth of the antenna could be designed according to the required specifications.

7.3.1.2 Patch antenna

Patch antennas are a very well-known antenna type that can also be designed for multiband deployments and can support dual polarization. The design is flatter when compared to a dipole antenna. Controlling the beamwidth is not as easy as with a dipole antenna, but nonetheless doable.

7.3.2 Low Gain isotropic NIB antennas

In this section, we explore different options for omni directional antennas. Three different structures have been studied: conformal patch antenna, sleeve dipole antenna, and combined directive antennas (combining 3-4 directive designs to obtain isotropic beam pattern).

7.3.2.1 Conformal patch antenna

In this design, the ground plane of the antenna is reduced to a tube, and the patch is wrapped around it. It is a very flexible and robust solution. It can be designed as an orthogonally polarized, higher gain version, multi band option on the same tube.

7.3.2.2 "Sleeve" Dipole or monopole antenna

Sleeve dipole (or monopole, if the structure has a ground plane) could be used as an omni directional antenna.

7.3.2.3 Combined antennas to build and omnidirectional beam pattern

An example would help the understanding of this concept. If we would combine 4 dual polarized patch antennas, we would get a quasi-omni directional pattern. Patterns could be controlled by the size of the ground plane as needed.

7.3.3 User Equipment (UE) antennas

UE antennas are specified as omni directional antennas. Some of the antenna options described for lander antennas may be used for UE antennas as well.

Two other antenna types are explored and proposed for UE antennas: patch antennas with changing polarization and helix antennas.

7.3.3.1 Patch antenna with changing polarization

This unique patch antenna has a very simple structure with a very wide frequency bandwidth. The disadvantage is the polarization purity. Due to its simplicity, compactness and wideband performance, this antenna could be a good candidate for EVA suits.

7.3.3.2 Helix antenna

A Helix antenna and its derivatives, like bifilar and quadrifilar helix antennas, are used in satellite and terrestrial mobile communications and WLAN routers. It is a very well-known type of antenna. For example, Quadri-filar helix antennas have been proposed for IRIDIUM satellite mobile devices using a very compact design.

7.3.4 Proposal for HLS/NIB Antenna architecture (360deg coverage)

Antenna placement on the HLS can greatly affect the coverage, since it establishes antenna height and possibly the direction of RF illumination (for the directive antennas)

The use cases described in Section 4 include the following scenarios:

- For short range, a full 360 degrees coverage is needed to support EVA around the HLS.
- For long range, multi km coverage is needed only in one direction that might not be known before landing.

For short range, therefore, isotropic antennas on the top of the HLS would be the ideal solution, while for the long range, a directive solution (pointing in the direction of interest) would be advisable.

However, the following limitations may arise from the HLS geometry and requirements:

- The top of HLS might not be available for mounting the isotropic antennas.
- The side of HLS might be the only available mounting place. The clocking angle after landing (and therefore the direction of interest for the directive antennas) might not be known "a priori".

While guaranteeing the needed short-range and long-range performance requirements, it is advisable to save weight and power and avoid coverage where not needed.

8 Network Performance Evaluation

8.1 RF Performance Evaluation

A Lunar surface communication coverage analysis is essential to support future lunar mission planning. 3GPP communications is envisioned between a 3GPP NIB integrated onto a lander/HLS, with height of either 15 or 30 m and a mobile unit or UE, with either a 4m high LTV or a 2m dismounted astronaut. A key impairment that potentially limits the coverage range is the terrain blockage. Nokia Bell Labs has developed a fast propagation modeling tool that takes a digital terrain map as an input and generates predicted path gain for the area. Other quantities needed for predicting communication performance, such as SNR and data rates follow directly. This report details the coverage estimate methodology and key results.

The predicted SNR and data-rates support communication capabilities to 10 km. The communication range is highly dependent on the chosen landing site and the surrounding terrain. While there are coverage gaps in certain areas or traverses, the feasibility of realistically being able to traverse those areas during a mission is evaluated by means of a terrain slope analysis.

8.1.1 Nokia Bell Labs propagation model

The path loss modeling methodology assumes that propagation is confined to the vertical plane containing the transmitter and the receiver, with the relevant terrain profile being defined by the intersection of the terrain elevation map and transmitted-received vertical plane. The resulting 2D propagation model is further simplified by approximating the wave equation by the parabolic wave equation, which can be solved numerically by a marching solution [1]. A faster alternative solution is followed in this work: the terrain profile between the transmitter and receiver is approximated by a parabola. The field from a point source over a parabolic-shaped boundary has an analytic solution parametrized by the curvature of the parabola allowing fast and direct evaluation [2]. This approach was tested against a large data set with about 3000 locations at ranges exceeding 5 km collected in open desert terrain in the Canary islands, Spain [3] in 2019, resulting in 8 dB RMS error for locally averaged receive power.

Additional heuristics were developed to improve accuracy, included raising the effective ground height by rms terrain undulations in the valleys and limiting path loss to “over-clutter” value [3]

8.1.2 Simulation assumptions

Table 13. Key simulation parameters

Parameter	Value
Bandwidth	20MHz
Center Frequency	2600MHz
3GPP UE (Astronaut/LTV) config.	2m/4 m antenna height, 5 dBi antenna gain Astronaut (23 dBm)/LTV (31dBm),2Tx-2Rx, Tx cable loss 1 dB
3GPP NIB (Lander) config.	15m/30 m antenna height 5 dBi antenna gain 36 dBm, 2 Tx x 2Rx, Tx cable loss 1 dB
Noise Figure	8.4 dB
Shadow Margin	10dB (90% for 8 dB shadow std dev, as in Parque Holandes, Canary Islands)

8.1.3 Simulation Results

The coverage from the Connecting Ridge Site 1 (CR1) location, (-89.468,222.6), near the Lunar South pole, is evaluated based on path gain, SNR, and rate "heatmaps" for different combinations of HLS heights (30/15m) and UE LTV/Astronaut heights (4m/2m).

8.1.3.1 Terrain elevation

The terrain elevation map, obtained from NASA Site 1[5], is illustrated in Figure 36 below:

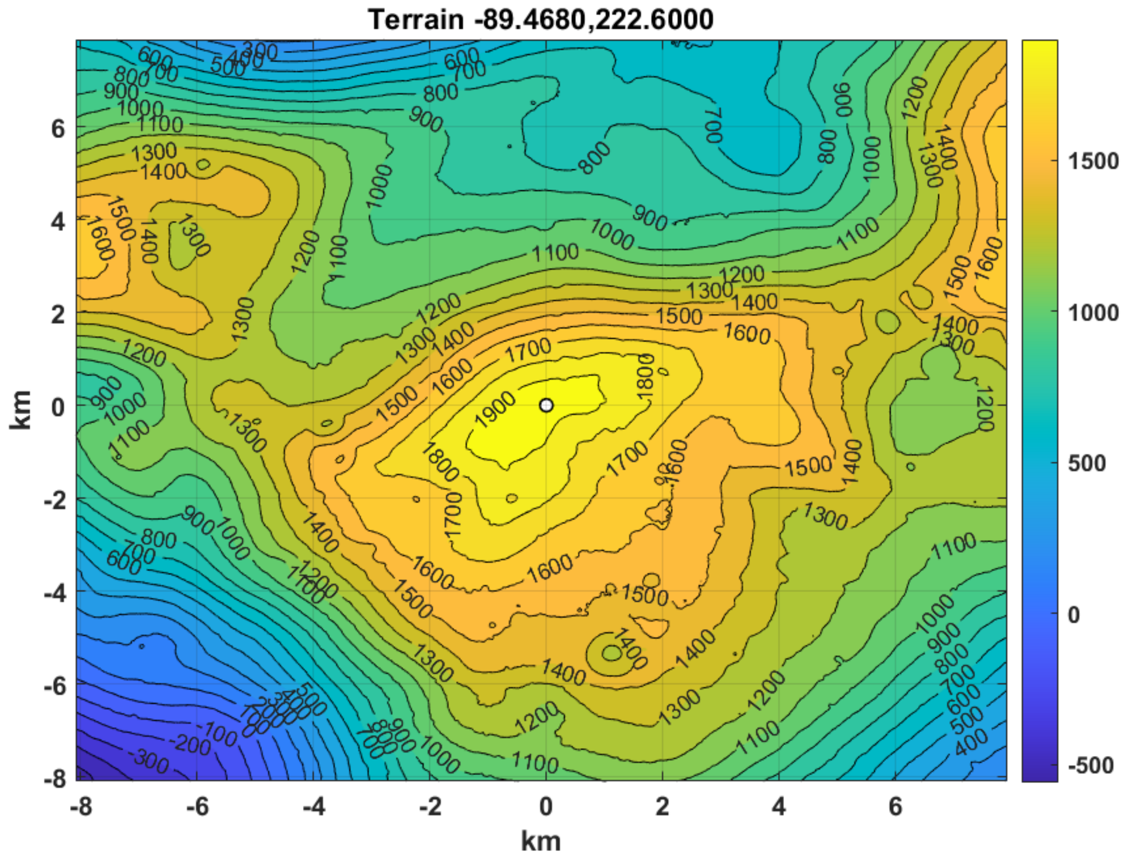

Figure 36 Lunar terrain elevation map centered on Connecting Ridge site.

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[5] https://pgda.gsfc.NASA.gov/products/78

8.1.3.2 Coverage for 15 m HLS lander

Results are shown below for the scenario with a 15m HLS lander and 2m UE (dismount height): Path gain map for 15m HLS lander and 2m UE is shown in Figure 37.

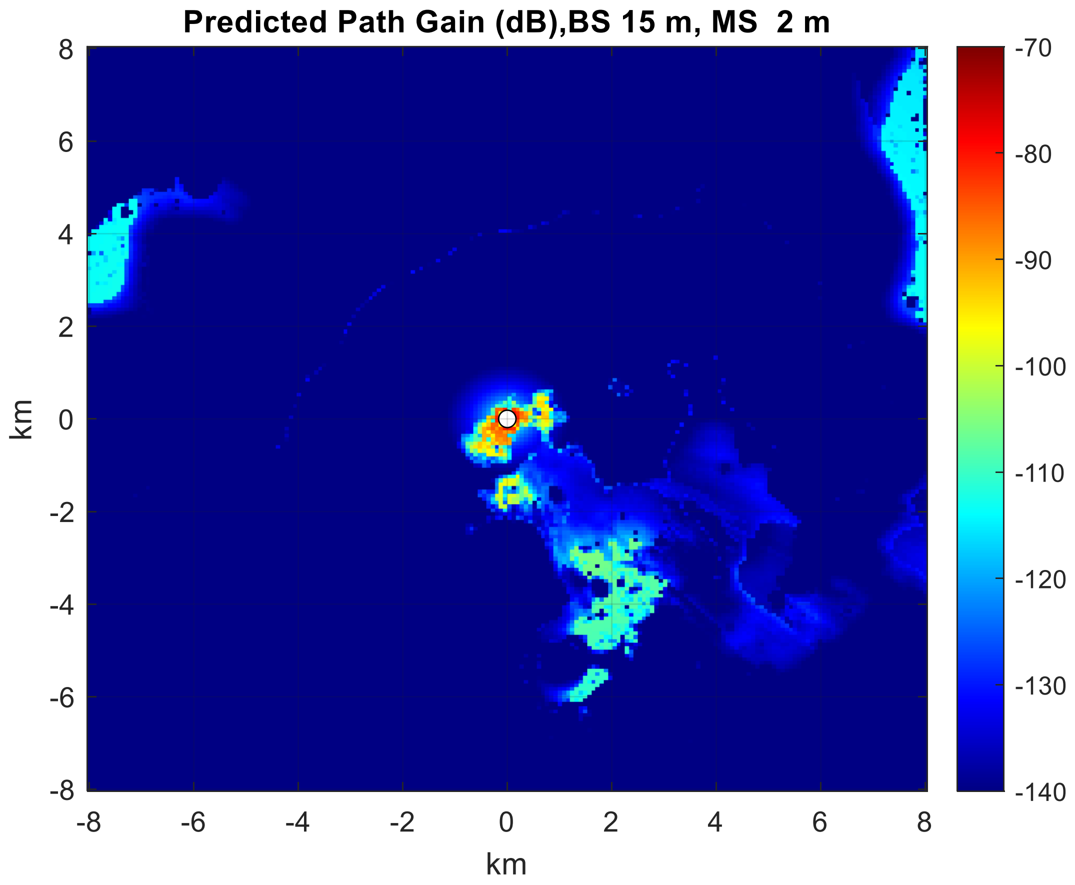


Figure 37. CR1 path gain, 15m lander, 2 m astronaut

The corresponding maps of downlink (DL) and uplink (UL) SNR and rate distributions are shown in Figure 38 and Figure 39, respectively. The coverage range is seen to strongly depend on the terrain direction. In the areas with gentler terrain slope in the upper part of the coverage plots, video rates (>10 Mbps) can be supported even at 10 km range. In other directions, where the steep terrain blocks the signal path, the coverage is restricted to about 1 km (e.g. lower left of map in Figure 38 and Figure 39).

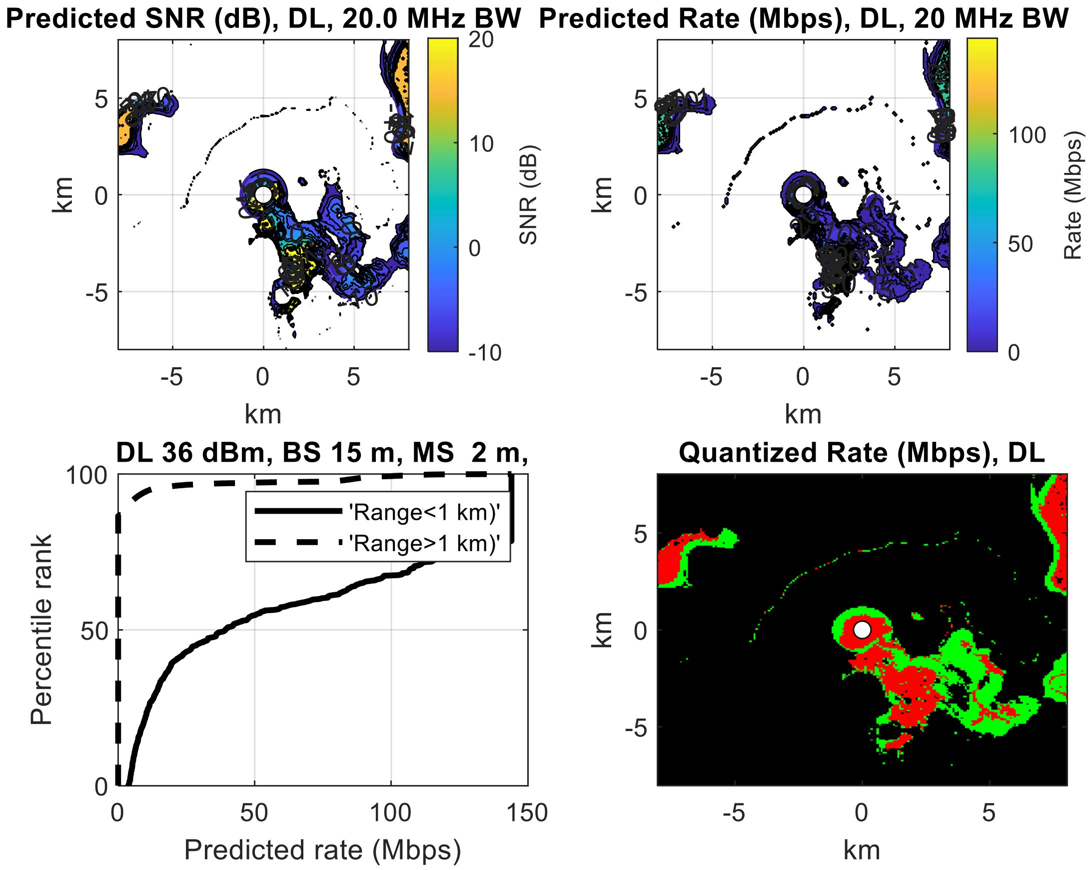


Figure 38. DL SNR and rate maps. Bottom-left quantized rates: Red: >10 Mbps (Video), 200 kbps<Green<10 Mbps (Voice), Black <200 kbps, 15 m lander, 2 m UE

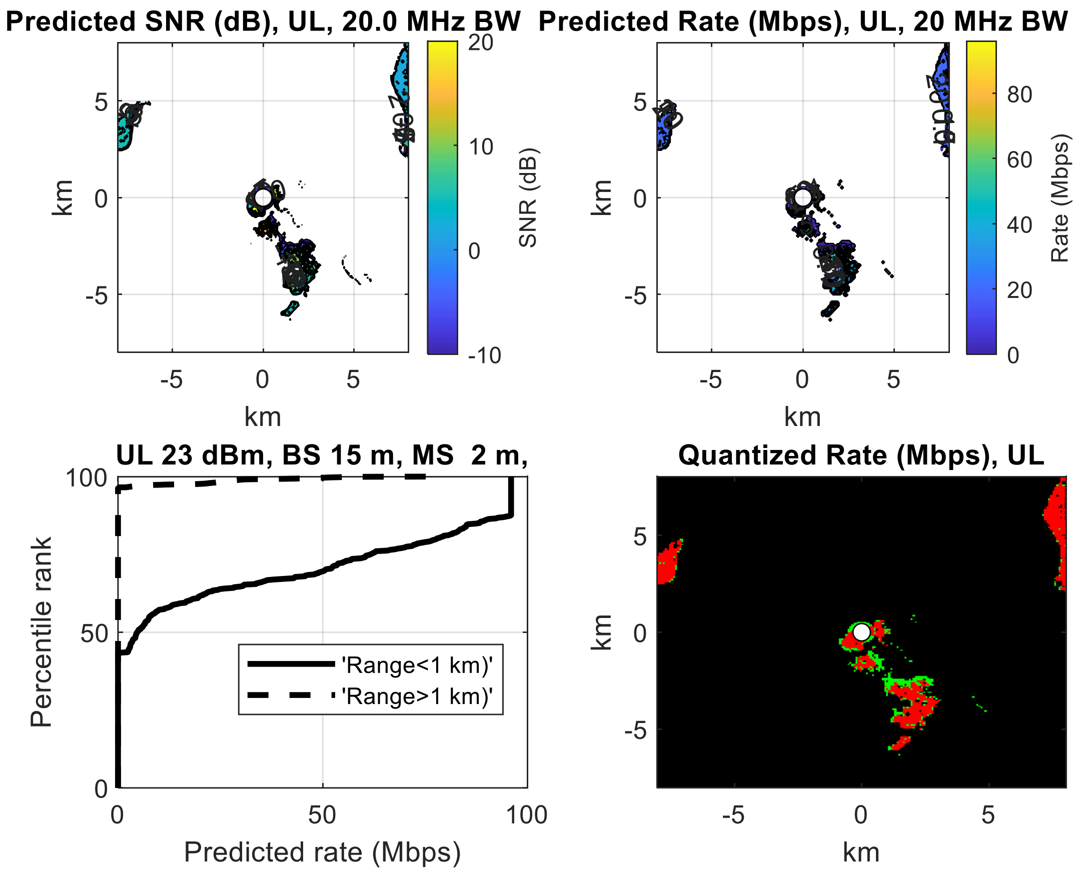


Figure 39. **UL SNR and rate maps, UL Tx power 23 dBm. Bottom-left quantized rates: Red: >10 Mbps (Video), 200 kbps<Green<10 Mbps (Voice),Black <200 kbps, 15 m lander, 2 m UE.**

8.1.3.3 30 m HLS coverage

The corresponding results are now summarized for the 30m HLS lander height.

Path gain map for 30m HLS lander and 4m LTV is shown in Figure 40.

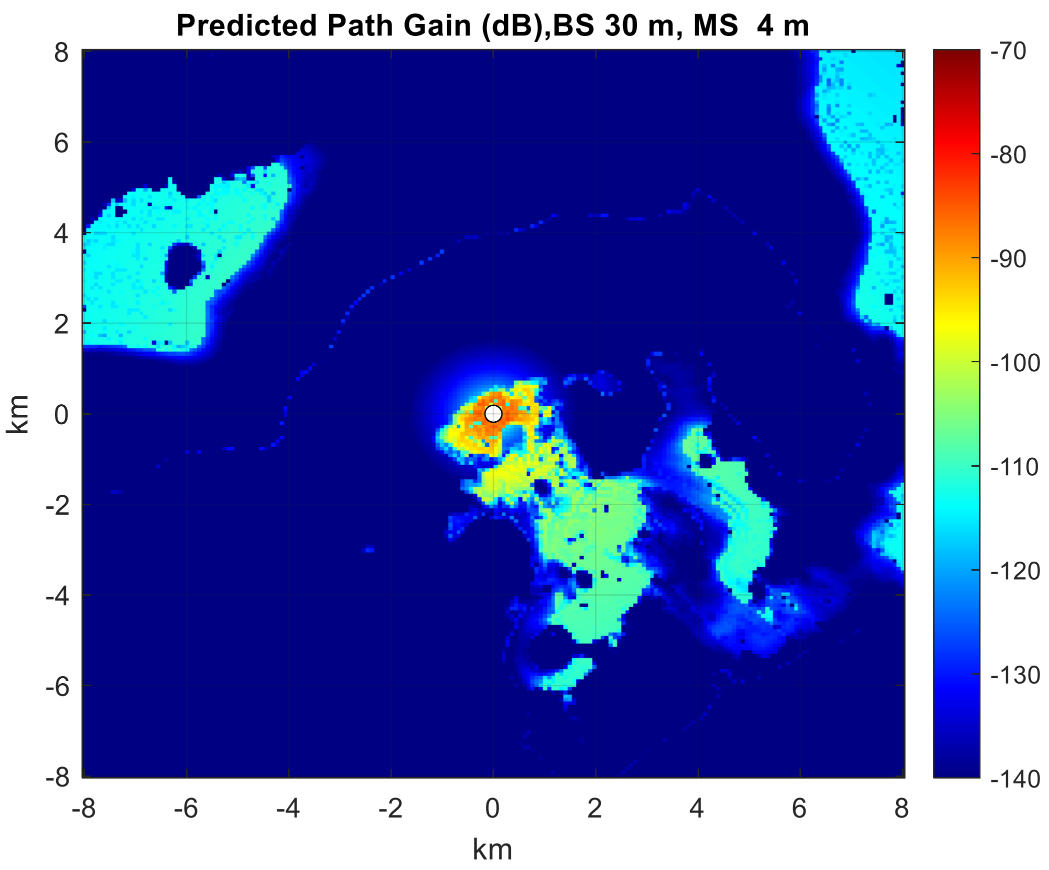


Figure 40. CR1 path gain, 30 m lander, 4 m LTV

The downlink (DL) and uplink (UL) SNR and rate distributions are shown in Figure 41 and Figure 42, respectively. The coverage range is seen to strongly depend on the terrain direction. In areas with gentler terrain slope in the upper part of the coverage plots, video rates (>10 Mbps) can be supported even at 10 km range. In other directions, where the steep terrain blocks the signal path, coverage is restricted to about 1 km (e.g. lower left of map in Figure 41 and Figure 42).

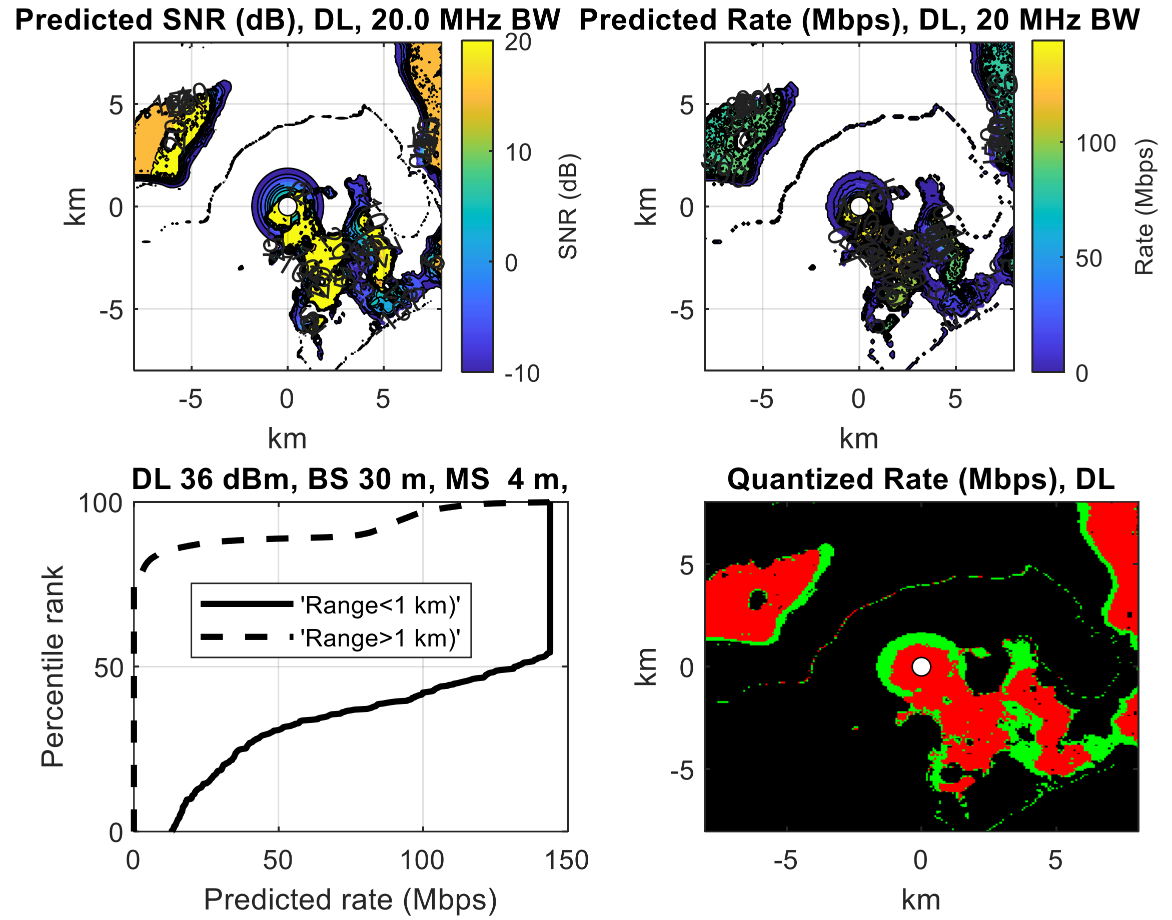


Figure 41. DL SNR and rate maps. Bottom-left quantized rates: Red: >10 Mbps (Video), 200 kbps<Green<10 Mbps (Voice), Black <200 kbps, 30 m lander, 4 m LTV.

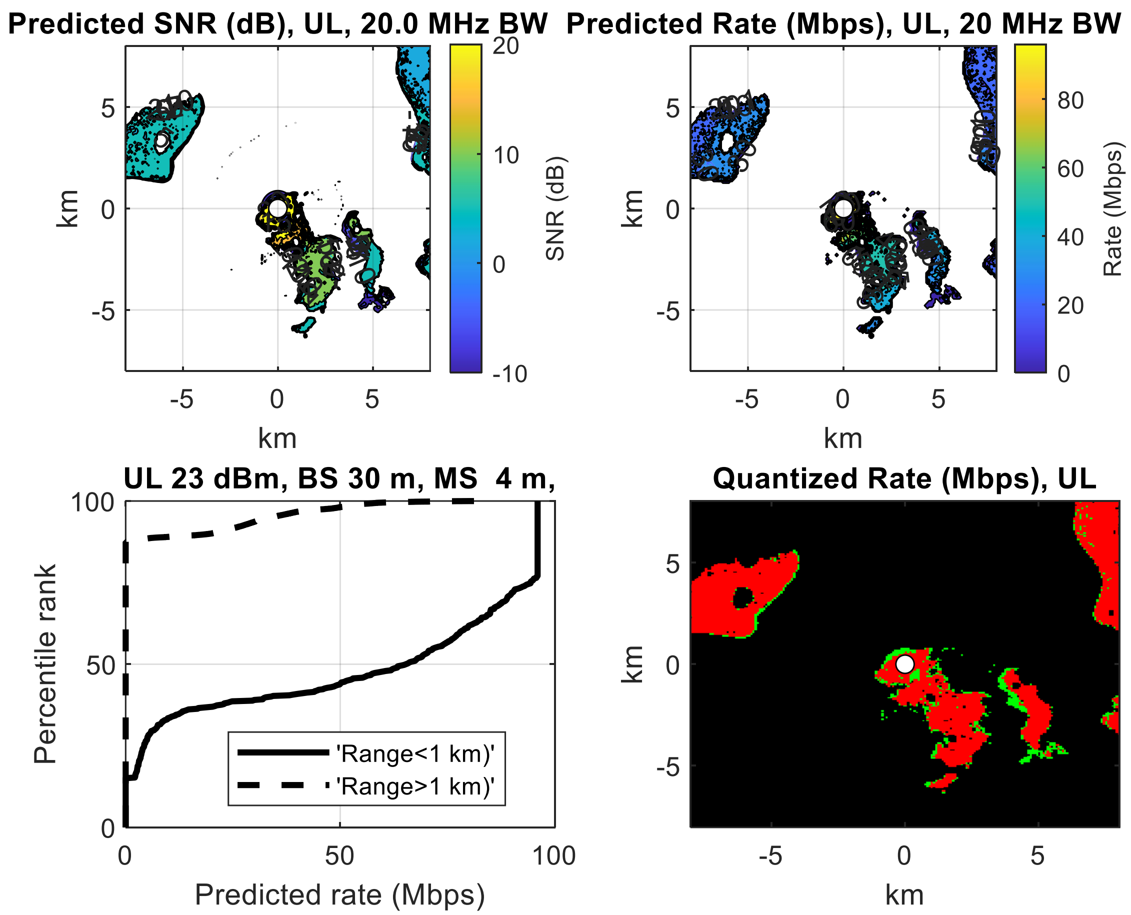


Figure 42. **UL SNR and rate maps, UL Tx power 23 dBm. Bottom-left quantized rates:** **Red: >10 Mbps (Video), 200 kbps<Green<10 Mbps (Voice), Black <200 kbps, 15 m lander, 4 m LTV.**

8.1.3.4 Terrain slope maps

The Lunar surface vehicle's ability to traverse the lunar terrain is in part determined by terrain steepness. A map of the terrain slope (defined as magnitude of terrain gradient) is plotted in **Figure 43**.

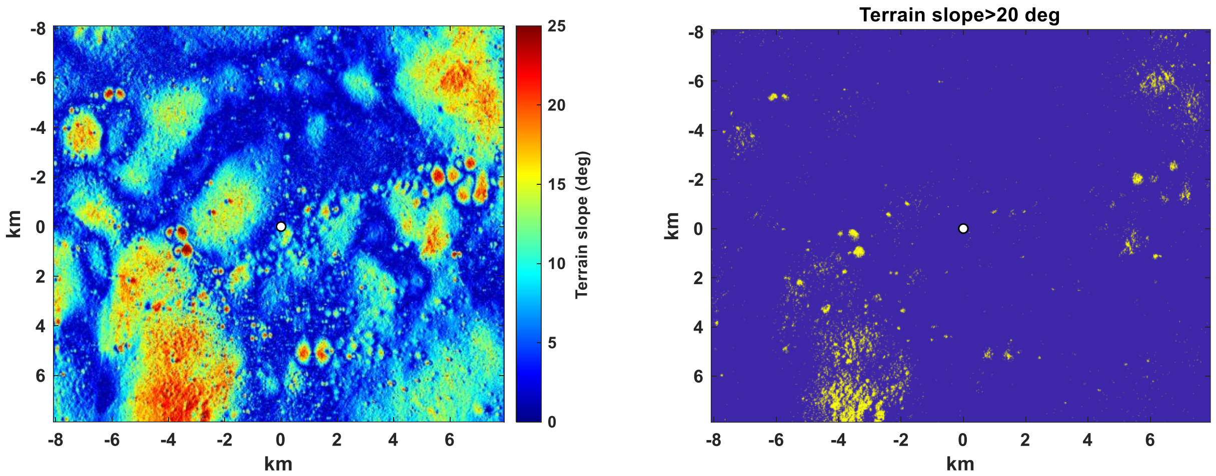


Figure 43. Terrain slope map (left). Quantized (right), yellow represents slope >20deg

Figure 44 provides a side-by-side comparison of the quantized slope maps (where dangerous areas from a high steep perspective are circled in red) against the predicted path gain for a 15m HLS lander and 2m astronaut height scenario. It is observed that some of the problematic/dangerous areas correspond to low path gain locations, where communications are not possible. For future mission planning, it is recommended to overlay both RF coverage maps with slope maps (and other key relevant factors such as lighting, Earth view, etc.) in order to carefully plan astronauts and rover traverses.

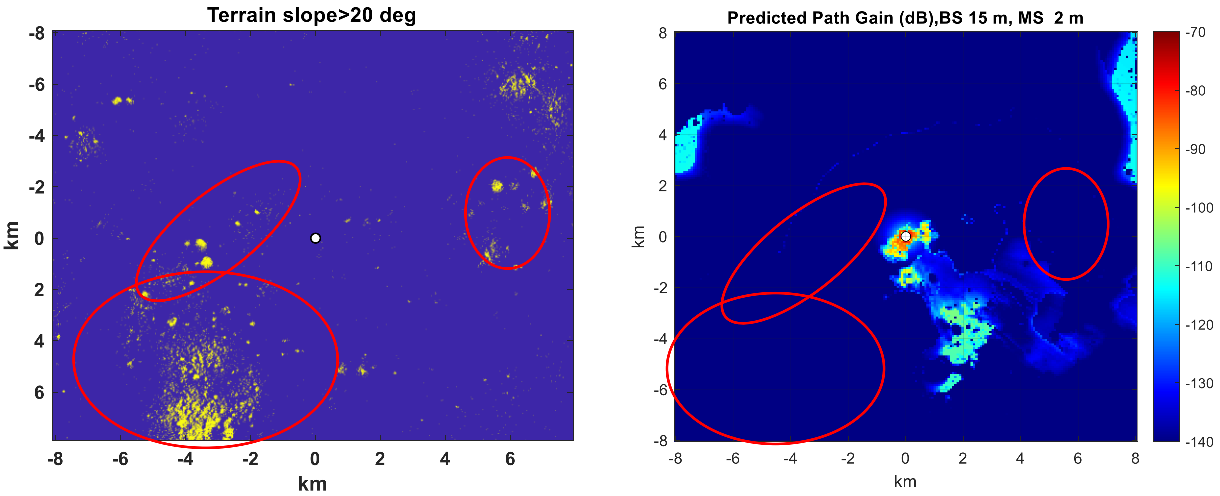


Figure 44. Side-by-Side Comparison of quantized slope terrain and path gain for 15m HLS, 2m Astronaut. Red circles represent dangerous areas from slope perspective

8.1.4 Conclusions

A Lunar surface communication coverage analysis is essential to support future lunar mission planning. 3GPP communications is envisioned between a 3GPP NIB integrated onto a lander/HLS, with height of either 15 or 30m and a mobile unit or UE, either an 4m high LTV or a 2m dismounted astronaut. A key impairment limiting the coverage range is possible terrain blockage. Nokia Bell Labs has developed a fast propagation modeling tool that takes a digital terrain map as an input and generates predicted path gain for the area. Other quantities needed for the predicting communication performance, such as SNR and rate follow directly.

- The predicted SNR and data-rates support communication capabilities to 10 km, supporting the Artemis V lunar scenarios covered in this study.
- The communication range is highly dependent on the chosen landing site and the surrounding terrain.
- While there are coverage gaps in certain areas or traverses, the feasibility of realistically being able to traverse those areas in a mission is evaluated by means of terrain slope analysis.

8.1.5 References

[1] A. E. Barrios, "A terrain parabolic equation model for propagation in the troposphere", *IEEE Trans. on Antennas and Prop.*, Jan. 1994.

[2] D. Chizhik et al., "Propagation Over Parabolic Terrain: Asymptotics and Comparison to Data", *IEEE Trans. on Antennas and Prop*, June 2010.

[3] D. Chizhik, J. Moilanen, S. Klein, L. Maestro, and R. A. Valenzuela, "Analytic Propagation Approximation over Variable Terrain and Comparison to Data," *2020 14th European Conf. on Antennas and Prop. (EuCAP).*

8.2 Localization Performance Evaluation

8.2.1 Overview

Determining the location of mobile assets on the Moon’s surface is an important technology that enables applications related to safety and process optimization. In this section, we study options for estimating the 2D location of assets that leverage the wireless communication systems (e.g., 4G LTE, 5G NR, 802.11 Wi-Fi).

Two assumptions are made regarding the general localization architecture based on the Artemis V use cases described in Section 4:

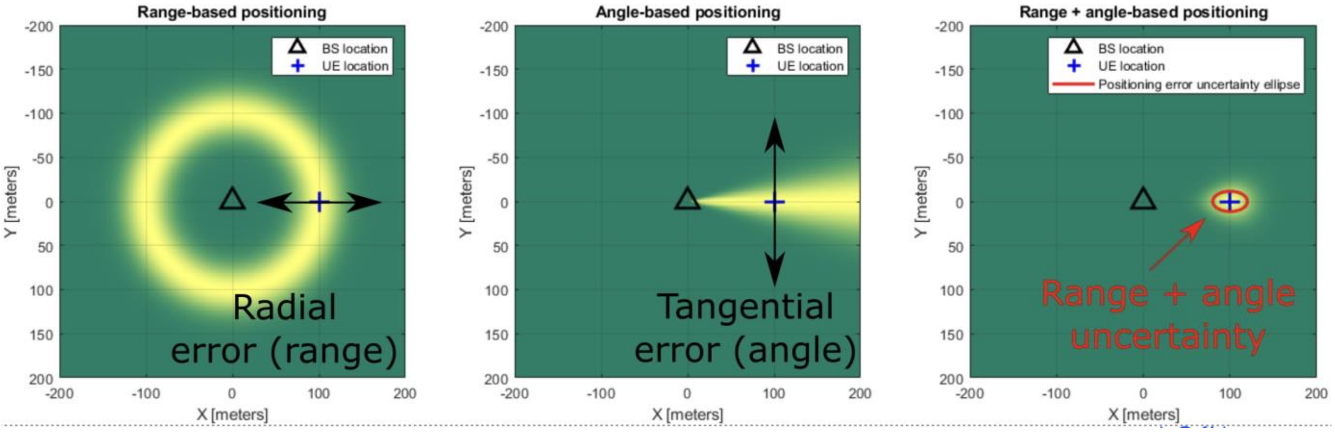
1) A UE on each mobile asset of interest (e.g., Astronaut EVA suit and/or LTV).
2) There is a single NIB infrastructure node co-located with the lander.

Note that while we consider both cellular and Wi-Fi systems, we will rely mostly on the cellular terminology of UE and NIB. We require that the 2D location of each UE is estimated with respect to the NIB location. The estimates should be acquired in real-time and with a maximum latency suitable for the application. For example, for tracking a vehicle moving at 3m/s, a reasonable latency would be on the order of 100ms to avoid collisions.

With only a single infrastructure NIB, 2D localization of the UE can be accomplished by combining range and angle estimates, where the range measures the distance from the NIB to the UE and where the angle is measured with respect to an arbitrary two-dimensional coordinate frame centered at the NIB. As shown in Figure 45, for a given range measurement, the angle is unknown, and for a given angle measurement, the range is unknown. A probabilistic 2D location estimate can be obtained by combining the two estimates. In addition to the position estimate, a reliability metric can also be obtained to characterize the quality of the estimate, e.g., a confidence 2-D ellipse.

In the sections below, we discuss techniques for range and angle estimation, including basic principles, implementation options for specific communication protocols, and performance-complexity considerations.

Figure 45. 2D localization with a single NIB using range and angle estimates.



8.2.2 Range estimation

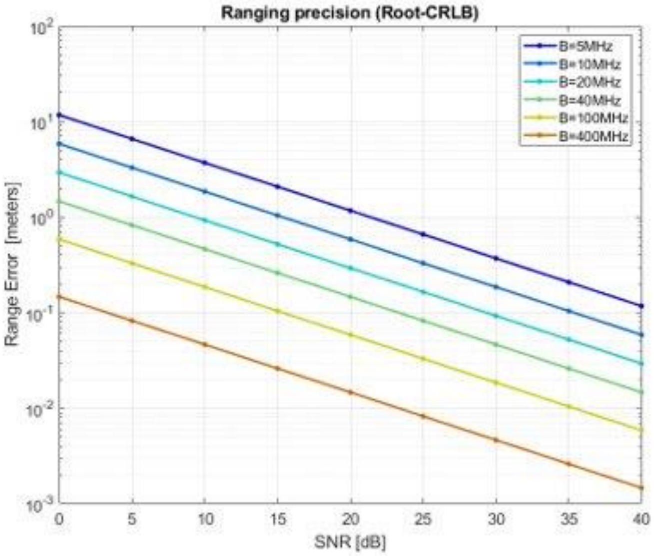
The goal of range estimation is to estimate the distance between the NIB and UE by processing uplink and/or downlink signals. We discuss fundamental principles and standards-specific techniques.

8.2.2.1 Range estimation principles

The distance or range *d* between a signal transmitter and receiver can be estimated by measuring an RF signal's strength or the time-of-flight. Due to the effects of multipath and shadow fading in the wireless channel, the bias and variance of the RF signal strength measurements are very high for a given distance and they degrade very quickly at larger distances. Hence the range estimate is very inaccurate and imprecise compared to measurements obtained from the time-of-flight.

The error performance of the time-of-arrival (ToA) estimate is measured as the absolute difference between the actual and estimated ToA. The theoretical lower bound on the estimator variance (the reciprocal of precision) is given by the Root Cramer Rao Lower Bound (RCRLB) [reference] which is inversely proportional to the product of the signal bandwidth and the square root of the received signal-to-noise ratio (SNR). Hence as the bandwidth or SNR increase, the variance of the ToA estimate decreases, and the error of the estimate is statistically lower. We note that for a given transmit power, the SNR is related to the range: the farther the UE is from the NIB, the lower the SNR. Figure 46 below shows the RCRLB range error as a function of SNR, parameterized by the signal bandwidth.

Figure 46. RCLRB range error as a function of SNR and parameterized by bandwidth *B*.



In practical environments (including the Moon), the channel will experience multipath fading in addition to the Gaussian noise. In this case, the received signal consists of the summation of the direct path's signal followed by multiple delayed and attenuated replicas of the same signal. Due to the scattering of the channel, the multiple propagation paths (rays) exhibit different lengths, hence their relative phases become random. Note that for range estimation, it is necessary to estimate the ToA of the direct LOS which corresponds to the first-arriving path, and not the delays of the multipath components that are received slightly later and are seen as disturbances. This produces a bias in the estimated ToA which results in an overestimation (or more seldom underestimation) of the range.

8.2.2.2 Range estimation in practice

The actual ranging estimation performance is further affected by constraints imposed by radio standards and limitations of practical RF hardware.

Timing advance based ranging

Under the 4G LTE standard, the only technique for range estimation for a single NIB is *timing advance*. Timing advance (TA) is a necessary process for synchronizing the NIB and UE such that the timing of the downlink and uplink slots at the NIB are aligned. In simple words, the NIB tells the UE when to transmit such that its uplink signal arrives at the NIB at the desired time instance. Technically speaking, the TA is a negative offset at the UE, between the start of a received downlink subframe and a transmitted uplink subframe. This offset accounts for the over-the-air signal time-of-flight between the UE and NIB, hence the range can be estimated directly by multiplying the TA by the speed of light.

The initial TA is set by measuring the uplink PRACH at the NIB. TA updates are based on the timing measurements of uplink signals including the PUSCH and PUCCH. The TA update is then sent on the downlink to the UE. The TA offset has a limited granularity defined in the LTE standard.

For both LTE and 5G NR, an additional timing alignment error (TAE) requirement states an absolute timing error between a NIB and any of its UEs.

In practice, the performance is affected by the actual NIB-UE distance (which affects SNR) and the multipath conditions. The theoretical limit established by the RCRLB is way too optimistic for most practical scenarios.

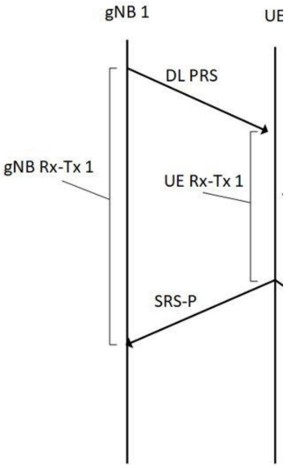
Round-trip time-based ranging

In 5G NR Release 16 standard, a number of new localization techniques were introduced, including multi-cell round-trip time, or *multi-RTT*. The technique enables much more accurate ranging estimation by measuring the time-of-flight for both uplink and downlink signals and computing the range based on half of the round-trip time.

Figure 47 below shows the RTT signaling between a NIB and UE. The RTT process starts with the NIB transmitting a downlink position reference signal (DL PRS) which is received by the UE. The UE then transmits an uplink sound reference signal (SRS) which is received by the NIB. If we let t1 be the time between the NIB PRS transmission and the NIB SRS reception and if we let t2 be the time between the UE PRS reception and the UE SRS transmission, then the time-of-flight can be estimated as the (t2-t1)/2. We note that RTT is independent of the NIB-UE synchronization. Therefore, RTT performance is not affected by the TAE.

Compared to TA, multi-RTT has superior ranging performance, but it has higher signaling overhead and has a slightly higher latency (on the order of 10s of ms) because both uplink and downlink signals need to be measured. For most localization applications, this additional latency will not affect the performance. Hence for 5G NR systems, we propose using RTT over TA because of the improved accuracy.

Figure 47. **Signaling for round-trip time range estimation**



Wi-Fi has a similar round-trip time estimator known as *Fine Time Measurements* (FTM) defined in the IEEE 802.11mc standard. For line-of-sight channel conditions, an 20MHz (and 80MHz) Wi-Fi signal can achieve ranging errors of about 8 meters (and 2 meters) [Reference]. However, compared to LTE, the practical range of Wi-Fi is limited to tens of meters due to lower transmit power.

SideLink ranging

Starting in 5G Release 18, a *SideLink* channel will be defined to enable UE-to-UE communication on either licensed or unlicensed spectrum. The SideLink channel can also be used for estimating the range between UEs, for example using RTT measurements. In principle, SideLink relative range estimates between UEs could be combined with NIB localization estimates to improve robustness and accuracy of their absolute positions. But this would come at the cost of additional signaling and processing.

Other performance impairments

Temperature variations can affect clock accuracy which in turn affects timing errors. These effects should be characterized for deployments on the Moon where temperature variations are more extreme than on Earth.

Computational requirements

Estimating the ToA requires an Inverse Fast Fourier Transform (IFFT) calculation whose complexity increases with the bandwidth of the SRS or PRS signal. This calculation is performed at the UE (for the PRS) or at the NIB (for the SRS), and typically would be implemented in the same specialized hardware used for physical layer computations.

8.2.3 Angle estimation

8.2.3.1 Principles of angle estimation

Estimating the angle-of-arrival (AoA) of a received signal can be achieved by jointly processing the signals at multiple elements of an antenna array. Angle estimation in RF systems most commonly uses a uniform linear array (ULA) of elements. If the received signal is modeled as a planar wavefront (which is satisfied if the distance between the transmitter and receiver is at least an order of magnitude larger than the antenna array size), then the carrier phase difference at each successive element of a ULA can be computed as shown in Figure 48 based on the distance d and the angle-of-arrival θ for an array with M elements. It can be shown that the delay at successive antenna elements is given by $2\pi(d/\lambda)\sin\theta$, Hence the complex phase shift at the mth antenna element relative to the first is $\exp[2\pi(m-1)\,(d/\lambda)\,\sin\theta]$, with $m = 1,\ldots,M$.

A receiver “beam” pointing in a direction γ can be formed by weighting the received baseband signal at the mth array element by the complex conjugate of the phase shift computed above and adding the M components. This process is also known as beamforming.

To estimate the AoA for a given received signal, the magnitude of the beamformer output is computed for different directions pointing directions γ, and the estimated AoA corresponds to the direction with the largest magnitude. Whereas the time resolution of depends on the bandwidth of the signal, the angle resolution of the beamformer depends on the antenna array aperture, which for a given inter-element spacing, is dictated by the number of elements.

Figure 48. Signal with angle-of-arrival θ received by a uniform linear array with M elements

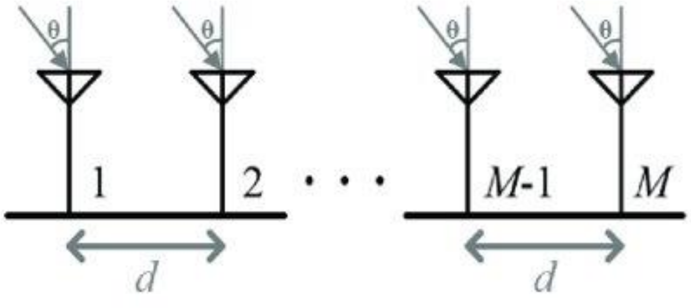


Figure 49 shows the magnitude of the beamformer output as a function of the pointing direction γ using a linear array with M = 2 omni-directional elements for signals arriving at θ = 0, 30, and 60 degrees. Figure 50 show the respective beam patterns for M = 4 omni-directional elements. We note how the beamwidth decreases with M and how the beamwidth increases as the angle-of-arrival increases. In other words, the angle estimation performance is the best if the signal arrives in a direction nearly perpendicular to the direction of the ULA.

Figure 49. Beamformer output for a ULA with *M* = 2 elements.

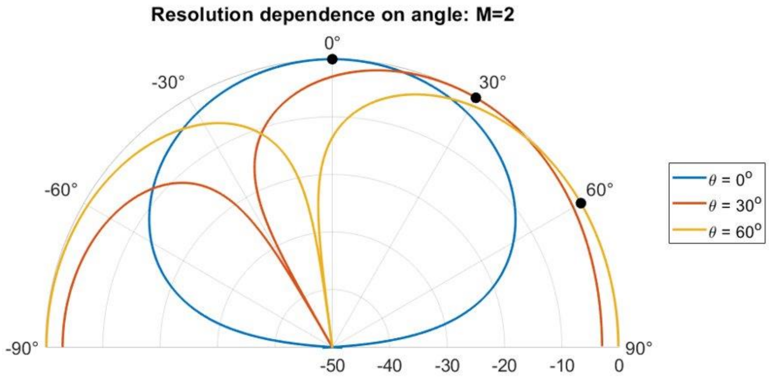
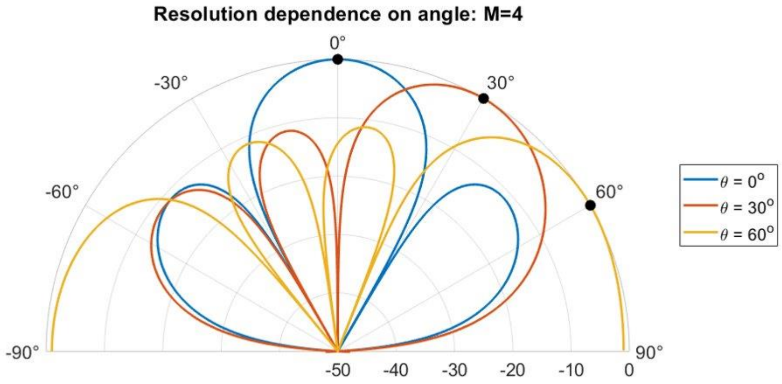
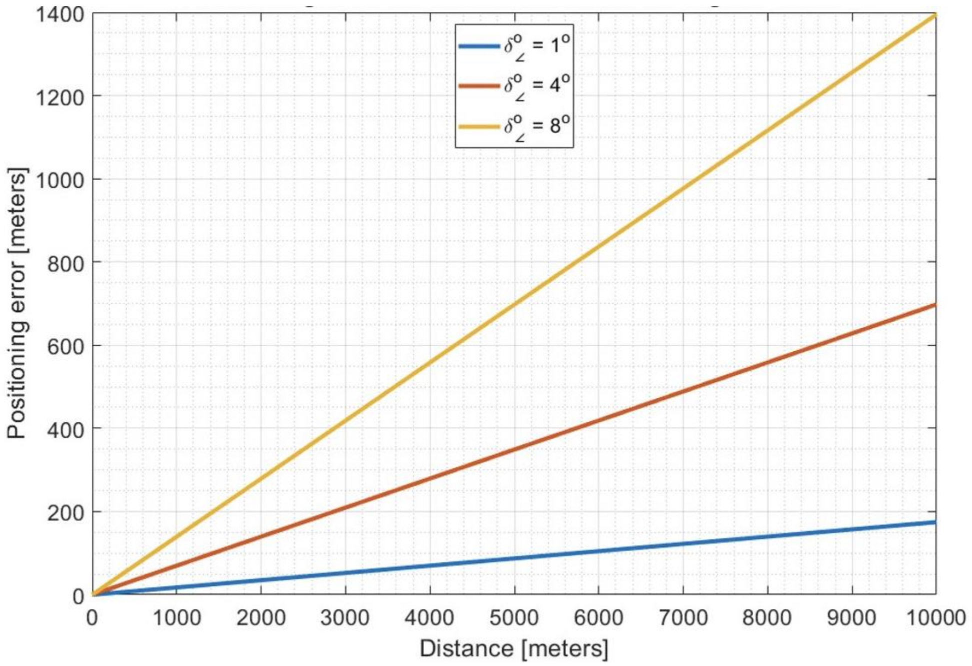


Figure 50. Beamformer output for a ULA with *M* = 4 elements.



Given some angular error, we can determine a tangential positioning error which is measured orthogonal to the line connecting the transmitter and receiver. Figure 51 below shows the tangential positioning error versus distance for angular error of $\delta = 1$, 2, 8 degrees. We may notice that the absolute tangential error increases with distance while the relative error with respect to distance remains approximately constant. We note that as the number of antenna elements increases, the angular error decreases. Hence from this figure we can conclude that at a given distance, the tangential positioning error qualitatively decreases with increasing number of elements.

Figure 51. Tangential error versus distance, parameterized by angular error δ.



Angle of departure (AoD) is an alternative to AoA in which multiple directed beams are transmitted using an array, and feedback from the receiver indicates which beam is received with the highest SNR. AoD requires more signaling than AoA, and its accuracy depends on the granularity of the beam directions.

8.2.3.2 Angle estimation in practice

Directional antennas

The discussion above assumed omni-directional antenna elements. If directional antennas (e.g., patch antennas) are used, each element will provide a narrower response. Therefore, combining across the individual elements will reduce the beam steering range. In one hand, this limits the coverage cone of the antenna, but also attenuates undesired multipath coming at high angles with respect to the antenna normal.

The tradeoff with directional antenna arrays is they cannot detect signals arriving from far outside their fixed direction of observation. This may not be a problem if the antenna array is at the edge of a site and all UEs will lie within the view of the directional antennas.

3GPP AoA estimation

In 3GPP 5G NR Release 16, new multi-cell positioning techniques were standardized for localizing UEs based on uplink angle-of-arrival estimates at multiple bases. The process could be used for uplink AoA estimation at a single NIB (and combined with RTT range estimation).

Computational requirements

Estimating the AoA requires search over some angular range and complexity increases linearly with the angular granularity assumed, which can be some fractions of a degree, and linearly with number of antenna elements.

8.2.4 Positioning performance prediction

In order to predict the positioning performance, we used Nokia's link-level simulator for different radio technologies: Wi-Fi (IEEE 802.11ac/mc), 4G LTE and 5G NR. The positioning results depend highly on the channel conditions, but the provided simulation shall approximate the predicted positioning errors much better as they rely on transmitted waveforms that exhibit realistic numerology, and reasonable hardware characteristics and propagation models (TX power, antenna gains, bandwidth, RX noise figure, path-loss, clock, and phase errors, etc.).

8.2.4.1 Simulation assumptions

We assume the following scenario and parameters:

- The SCR2b landing location (lat=-89.4876; lon=-138.2528) based on paper by Dmitry Chizhik *et al.* [1]
  [1] D. Chizhik, J. Moilanen, S. Klein, L. Maestro and R. A. Valenzuela, "Analytic Propagation Approximation over Variable Terrain and Comparison to Data," EUCAP, 2020.
- NIB height = 4 meters
- UE height = 1 meter
- Sectorized antenna with 4 sectors (1 uniform linear array/sector)
- Number of antenna elements/array (typical values):
    - Wi-Fi: 4 elements
    - 4G: 4 elements
    - 5G: 8 elements
- Carrier frequency / bandwidth / TX power:
    - Wi-Fi: 2.45 MHz / 20 MHz / 17 dBm
    - Wi-Fi: 5.17 GHz / 80 MHz / 17 dBm
    - 4G: 2.5 GHz / 20 MHz / 36 dBm
    - 5G: 2.5 GHz / 100 MHz / 36 dBm

8.2.4.2 Simulation results

We evaluated the radial positioning errors (or ranging error) and the tangential positioning error (caused by the angle estimation errors) for the considered radio technologies (Wi-Fi, 4G and 5G) and represented them as *boxplots*.

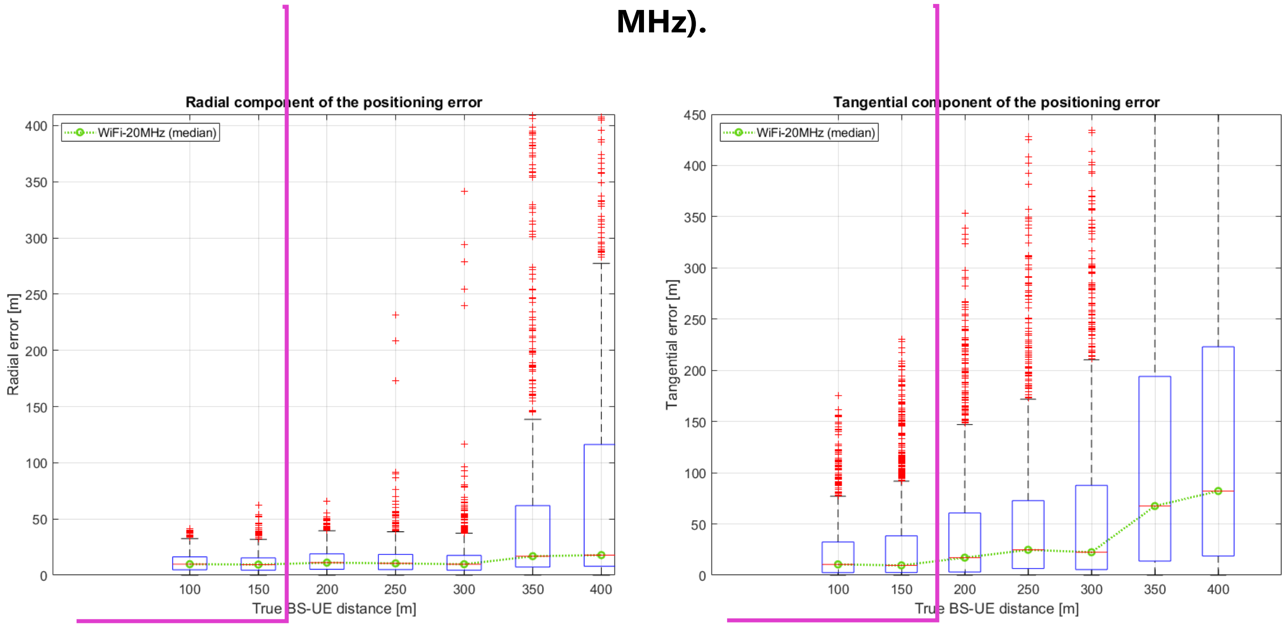
Note on how to interpret a boxplot (from the MATLAB® help as explained by Mathworks): "*On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme datapoints the algorithm considers to be not outliers, and the outliers are plotted individually.*"

The results are shown in Figure 52 to Figure 56, where we may notice that both the radial and tangential errors increase with distance, The radial error degrades with distance primarily due to the lower SNR. The tangential error exhibits two different degradation mechanisms vs. distance. Apart from the natural degradation of angular estimates with the distance due to lower SNR, additional degradation takes due to geometry. Such degradation takes place because for a fixed angular error, the tangential positioning error increases linearly with distance. This fact was observed previously in Figure 51.

Figure 52 and

Figure 53 show the degradation of radial (left subplot) and tangential (right subplot) positioning errors with distance as boxplots for Wi-Fi (20 and 80 MHz bandwidth, respectively). The median error is shown by the green dotted lines (meaning that half of the positioning errors will be below that value, and the other half above it). In practice, the achievable Wi-Fi range is very limited, typically to 50-150 meters. In the most optimistic case it may reach at most 250-300 meters (in perfect LOS conditions, see e.g. here). Therefore, this positioning technology may be used only in the immediate vicinity of the Wi-Fi AP (lander). We also noticed that the difference between 20MHz and 80 MHz bandwidth is negligible.

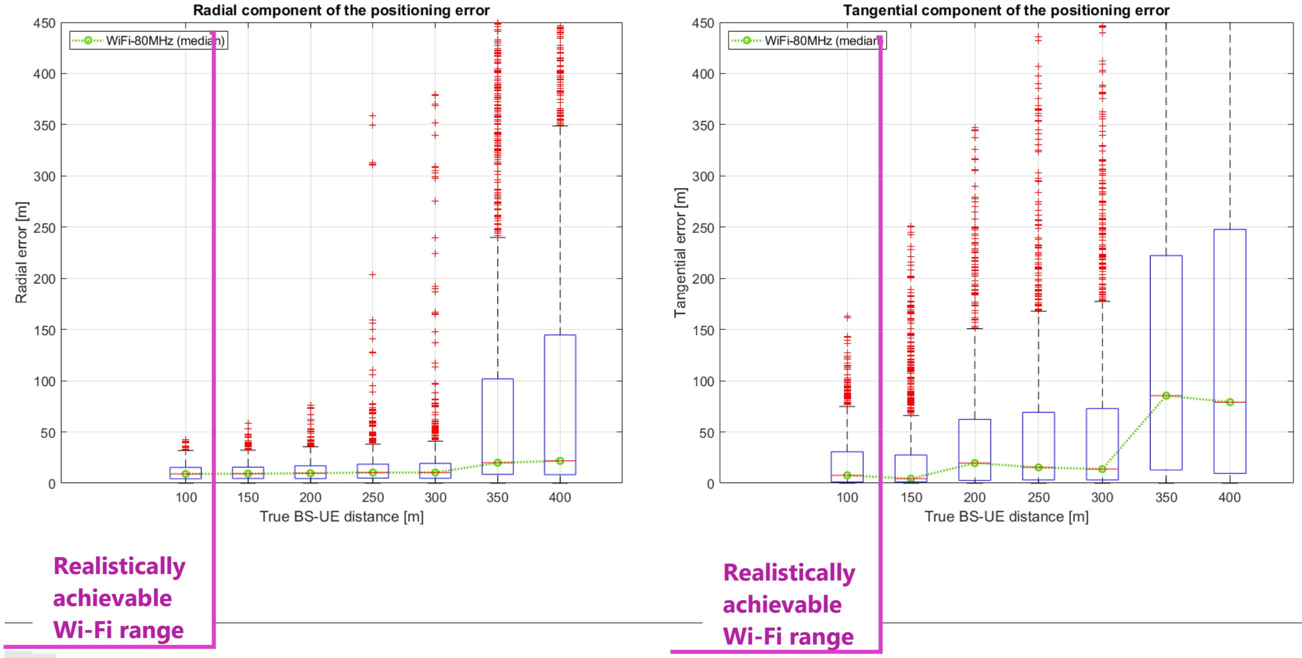
Figure 52. Radial and tangential positioning error vs. true distance for Wi-Fi (*B* = 20 MHz).



Realistically achievable Wi-Fi range

Realistically achievable Wi-Fi range

Figure 53. Radial and tangential positioning error vs. true distance for Wi-Fi (*B* = 80 MHz).



Realistically achievable Wi-Fi range

Realistically achievable Wi-Fi range

Figure 54 shows the degradation of radial (left subplot) and tangential (right subplot) positioning errors with distance for 4G LTE as boxplots. The median is shown by the green dotted line. We may notice a substantially extended coverage of LTE compared to Wi-Fi, and a superior positioning performance at very large distances (the 4G predicted median ranging error is around 100 meters at 8 km away, but there is a high error variance).

Figure 54. Radial and tangential positioning error vs. true distance for 4G (*B* = 20 MHz).

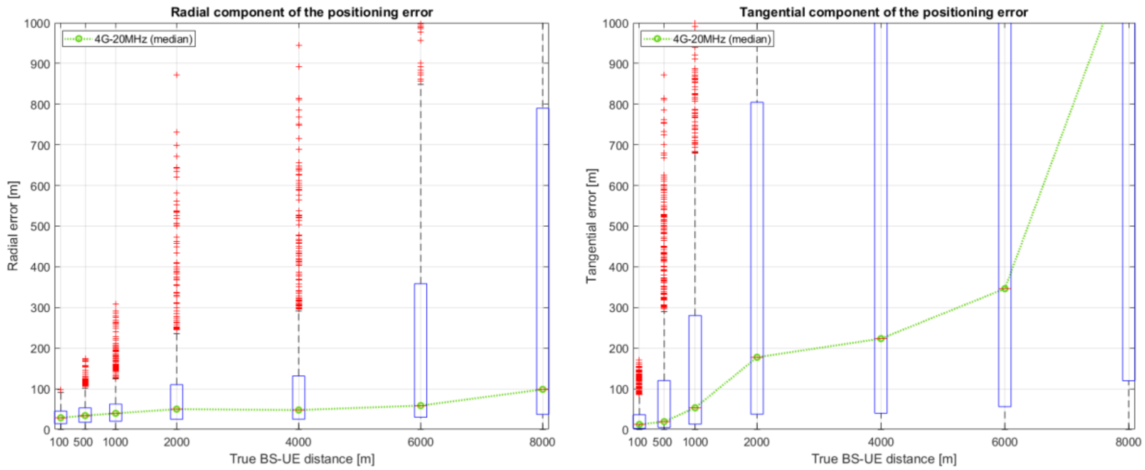


Figure 55 shows the degradation of radial (left subplot) and tangential (right subplot) positioning errors with distance for 5G NR as boxplots. The median is shown by the green dotted line. We may notice a substantially extended coverage of 5G (comparable with 4G), and a slightly better positioning performance compared to 4G (the 5G predicted median ranging error is around 50 meters at 8 km away, and the error variance is also lower).

Figure 55. Radial and tangential positioning error vs. true distance for 5G (*B* = 100 MHz).

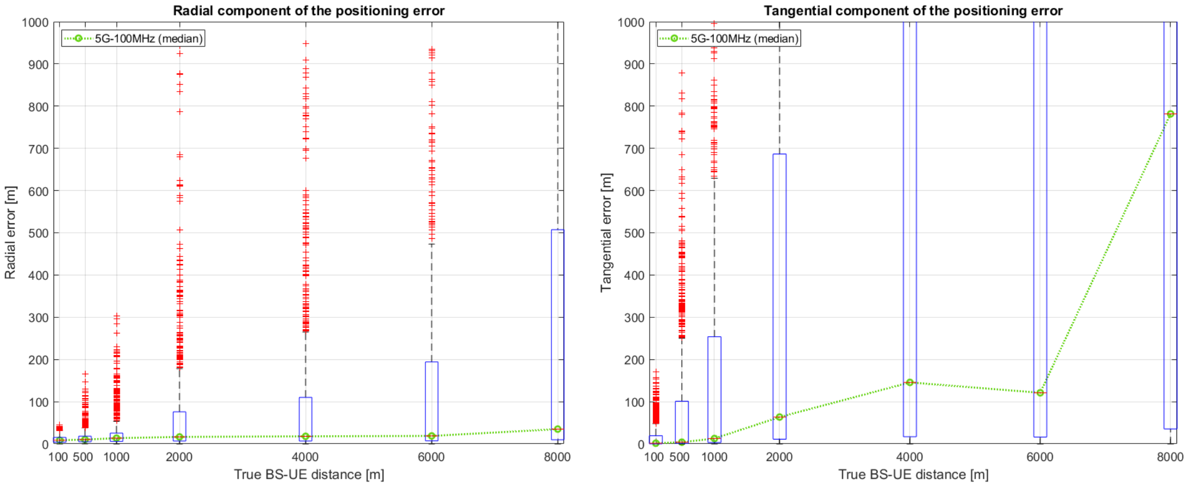
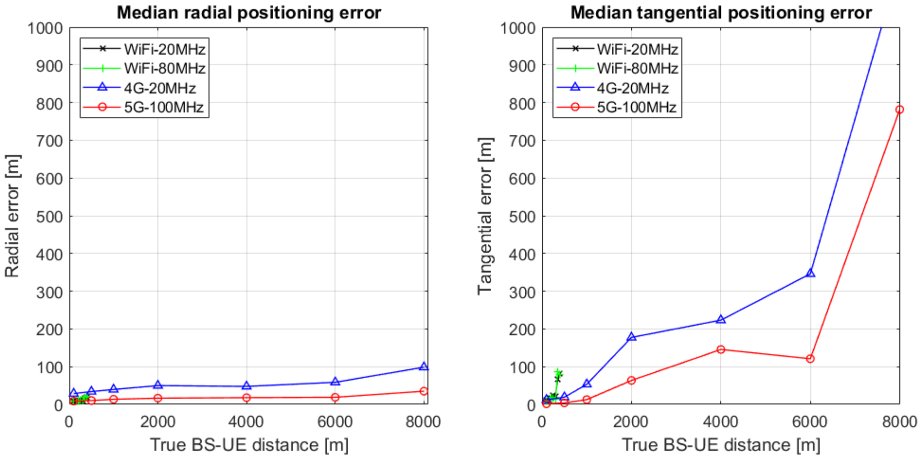


Figure 56 summarizes the results by showing only the median radial and tangential errors on the same subplots. We now may notice the extremely limited range of Wi-Fi (barely visible at this scale) compared to 4G and 5G. The 5G technology shows a radial positioning error relative to the true distance in order of few percent, whereas the relative tangential positioning error relative to the true distance in order of 10%.

Figure 56. The median of radial and tangential positioning error vs. true distance for different radio technologies.



9 Hardware Reliability Assurance

9.1 Introduction

The study is limited to lunar surface applications only. Non-lunar environments and any detailed reliability plans for a contracted program are out-of-scope. The specific UE and antenna design details associated with the EVA suits are covered in the 3GPP UE and RF Antenna Sections. While the general UE hardware reliability aspects are covered here, specific details relative to thermal behavior and reliability of the EVA suit hardware are considered design specific and are thus not included in this feasibility study. The E2E Architecture section includes discussion of use cases, fault tolerance to network/NIB and UE failures, and Network Resiliency.

9.2 HW Reliability Requirements

9.2.1 High Level Requirements

Reliability requirements were provided by NASA and shared with Nokia as basis for the subsequent analysis.

9.2.2 Supporting Standards

A partial listing of relevant, publicly available standards associated with the requirements is included here. The most recent versions should be used.

- ANSI/ESD S20.20: For the Development of an Electrostatic Discharge Control Program for - Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices)
- IPC J-STD-001GS: Space and Military Applications Electronic Hardware Addendum to IPC J-STD-001G Requirements for Soldered Electrical and Electronic Assemblies
- IPC-2220 series per Performance Class 3: Family of Printed Board Design Documents 2221:B, 2222:A, 2223:D, 2224:BL, 2225: BL, 2226: BL
- IPC-6010 Series: Family of Printed Board Performance Documents 6011: BL, 6012: DS, 6013: C, 6015: BL, 6017: BL, 6018: CS
- MIL-STD-981: Design, Manufacturing and Quality Standards for Custom Electromagnetic Devices for Space Applications
- NASA-STD-1008: NASA Classifications and Requirements for Testing Systems and Hardware to be Exposed to Dust in Planetary Environments (to be confirmed)
- SMC Standard SMC-S-016: Test Requirements for Launch, Upper-Stage, and Space Vehicles

- SMC-S-010: Space and Missile Systems Center Standard, Parts, Materials, and Processes Technical Requirements for Space and Launch Vehicles, only EEE parts sections
- NASA-STD-8739.10: Electrical, Electronic, And Electromechanical (EEE) Parts Assurance Standard
- GSFC-STD-7000b: General Environmental Verification Standard
- ECSS-E-20-01C: Multipaction design and test
- ESCC 22900: Total dose steady-state irradiation test method
- ESCC 25100: Single event effects test method and guidelines
- EIA/JESD57, Test Procedures for the Measurement of Single-Event Effects in Semiconductor Devices from Heavy Ion Irradiation

9.2.3 Fault Tolerance

To achieve 2FT, full redundancy is required for both the NIB and the UE. Issues relevant to 2FT from a safety requirements perspective were not identified at the time of this study, are mission dependent, and will require additional evaluation.

9.2.4 Hardware Reliability

Reliability of a redundant NIB and a redundant UE was first estimated to determine the likelihood of meeting the system reliability target. A commercial off the shelf (COTS) single redundant NIB likely does not meet the target MTBF requirement unless replacement is performed at an interval less than 10 years. Use of a combination of "space grade", upscreened, and automotive components will improve MTBF estimates since the quality levels of these parts will result in higher MTBF values, as will adoption of the more stringent derating practices used by the space industry.

9.3 Components

Telecom equipment providers predominantly use COTS components so will have to identify components available as space grade or approved for space use to meet the criticality one requirement. Many of the COTS components are readily available as space grade parts. In addition to meeting the criticality one requirement, use of space grade parts will also improve the MTBF estimated values. However, there are some COTS components used in terrestrial products that are of potential concern when converting to space applications. With respect to digital components, it is likely that the latest semiconductor technology nodes implemented on COTS components are more resistant to radiation than older technologies were due to both changes in transistor design and materials used. It will be important to characterize radiation performance. Options available to consider for component replacement include:

1. Full reuse of commercial hardware designed and assembled using COTS parts as is. In general, this approach won't meet the stated NASA requirements, so it is not recommended, at least not for every component. The following approach is preferred.
2. Use qualified space/military components already on the QML (qualified manufacturer's list) as much as possible. When qualified components (preferred) are not available
    a. Use automotive parts when available; however, some critical components, such as the UE modem chipset, may be available as an automotive part and still require careful evaluation and additional testing, especially with respect to radiation characterization.
    b. When automotive parts are not available, upscreen the components.

9.4 Material and Process Requirements

9.4.1 Pb-free requirements

The main gap between telecom and NASA material requirements is that manufacturers of commercial telecom equipment do not typically meet NASA requirements limiting use of Sn (tin) in solders and finishes. This is due to the widespread acceptance of Pb-free component finishes (with some limitations and test controls in place) and Pb-free solders to meet customer material requirements forbidding the use of Pb (lead). Adopting SnPb (tin-lead) finished components and SnPb assembly is likely the lowest risk (and highest cost) option.

9.4.2 Outgassing Requirements

Materials may also be required to meet low outgassing requirements. Outgassing is not generally expected to adversely affect the telecommunications hardware, but may deposit on any sensitive nearby equipment, and could also adversely impact thermal performance.

9.4.3 Conformal Coating

Telecom equipment suppliers have some experience using conformal coatings in targeted applications, but most do not routinely use them due to both cost and the difficulties it causes in test and repair of returned hardware. The materials used for terrestrial applications are not usually qualified for space applications and may not meet outgassing requirements. For lunar operation, the primary purpose of a conformal coat is for protection against dust during lunar operation. Precautions are usually taken to preclude dust entry into electronics enclosures, but dust can enter electrical circuit areas even with these precautions.

9.4.4 Cleanliness Requirements

Cleanliness requirements are mission dependent. They are included here because NASA requirements will differ from standard telecom requirements, and providers will incur some additional cost to meet them. Third party suppliers can be readily subcontracted for the work.

9.5 Parts Assurance/Controls

Parts assurance/control procedures used by telecom equipment providers are likely to be less stringent than those required by NASA. While use of NASA/DoD parts and approved assemblers should enable requirements to be met and alleviate some schedule implications, additional control requirements will likely require implementation. The telecom supplier should carefully review practices vs requirements and allocate resources for doing this.

9.6 Reliability Testing

Testing should follow recommendations in GEVs (General Environmental Verification Standard, GSFC-STD-7000, latest revision) and include, as appropriate, acceleration, shock, vibration, thermal cycling, thermal-vacuum, EMC/EMI as well as multipaction and PIM evaluation/testing. Thermal-balance testing is addressed in the thermal-mechanical design. Many of these tests differ from those commonly used throughout the telecom industry. Vacuum and multipaction testing will be new to the telecom industry, and dynamic and the EMC/EMI test requirements differ from those required by current telecommunication standards. Thermal requirements may also vary, and strict thermal control may be required. When missions last through the lunar night, a heat source will be required. For the purposes of this study, the heat source for overnight survival is assumed to be provided by a third-party qualified solution and was not further investigated. In addition to the forementioned tests, long term reliability testing/assessments are potentially required for some components and assemblies, but use of qualified components/assembly techniques should minimize that need.

In general, for radiation susceptible components, parts should be selected for which suppliers can provide radiation test data. Depending on the availability of component radiation test data, additional radiation testing is most likely required, inclusive of TID, proton, and heavy ion testing. These test programs have long lead times, mostly due to the lead times for beam time.

The UE modem will employ a chipset that is not strictly “space-grade”. Such chipsets consist of several blocks of different functionalities optimized for the small form factor and low energy consumption; re-designing such a complex integrated system would be prohibitive and would require a very deep knowledge of several subsystems and sizeable development resources with no guarantee of success. Qualification of COTS parts is a better alternative.

In this study, it has been determined that there are COTS parts available from some suppliers for which significant radiation test data is already available. For example, JPL has characterized radiation effects on specific automotive grade SoCs similar to those used in terrestrial mobile phone devices and successfully deployed them on the Mars Ingenuity helicopter and the ISS.

Thus, Nokia has concluded that solutions for the UE modem are likely available but strongly recommends starting a thorough radiation test program for modem solutions as soon as possible.

In general, it is recommended to only use suppliers who can provide radiation test data. However, even use of those components for which radiation test data is available will require the telecom supplier to understand how the NIB and UE systems respond to radiation and employ suitable mitigations to limit the impact of radiation effects such as SEE.

Many suppliers will be able to provide SEE test data for COTS/automotive parts built using a specific process. Data is unlikely to be available on a per part basis but will be available on a technology level/fabrication line basis. TID data may not be available.

9.7 Conclusions

- Implement redundancy for NIB and UE.
- Procure space qualified or automotive qualified parts as much as possible, with additional upscreening and/or selective testing as required. The expectation is that most components will be available. However, there will be impacts on SWaP due to the switch from COTS.
- Any components not on the DoD/NASA approved lists may need to be re-finished.
- While a UE modem chipset may have some space/radiation tested components available, additional component level and system level radiation testing will be needed to characterize and mitigate impacts from radiation. It is recommended to start a radiation test program as soon as possible.
- PCBs shall be designed using IPC Class 3 design rules rather than the Class 2 design rules commonly used in the telecom industry.
- Designers will need to be trained on NASA derating guidelines and tools developed or deployed to assist in derating analyses.
- Telecom providers will need to perform reliability tests that differ from those common throughout the telecom industry, in particular vacuum and multipaction testing will be new to the telecom industry, and dynamic and EMC test requirements will be different.
- Telecom equipment providers will need to review, assess, and implement changes where necessary for parts assurance/control, traceability, to assure compliance with NASA requirements.

10 Software Architecture and Reliability

10.1 Software Classification

In a space communication system, software (SW) can be categorized into following categories based on where it is being used:

- SW running in FPGA or ASIC/SoC
- Firmware
- Operating System
- ‘Regular’ SW

It can be argued whether code/logic running in an FPGA or an ASIC counts as SW, but to give a complete picture, those are included here. SW can also be categorized into the following logical entities:

- Network in a Box (NIB)
- User Equipment (UE)
- Management SW (O&M)

10.2 Software Criticality

In context of this study, we concentrate on the voice and video communication involving astronauts, but the same principles can be applied also to regular data and telemetry transfer.

Since software running in NIB and UE are directly involved in data path for the voice and video communication, it is considered *Safety Critical*.

Even though the O&M SW is not directly needed for communication with astronauts, it is used to manage and monitor SW used in such communication. Thus, it can also be considered *Safety Critical* as per NASA classification and must meet strict verification requirements.

10.3 Software Verification Requirements

NASA has very vigorous verification requirements for *Safety Critical* SW.

These are described e.g. in following documents:

- NASA-STD-8739.8 – Software Assurance and Software Safety Standard
- NPR 7150.2D – NASA Software Engineering Requirements

All the SW running on the NIB and the UE must be verified, even if it is proven and legacy from terrestrial networks.

If the NIB and UE are based on Free and Open-Source Software (FOSS) or contain FOSS, FOSS needs to be certified also.

10.4 Proposed Approach

Verification of code running in FPGAs and ASICs can be quite costly and take a lot of time.

We are proposing to verify and trace SW that is specifically built for the space missions, i.e. additional requirements and their implementation, beyond available SW from terrestrial network solutions.

However, it is to be noted, that a comprehensive end-to-end SW integration and testing plan is expected to be implemented, including provocative test cases and corner-case scenarios to ensure that the end-to-end system performance is according to the requirements.

11 Spectrum and Frequency Planning

The Space Frequency Coordination Group (SFCG) has been established with the scope of managing and resolving, in collaboration with the ITU, the use of RF frequencies in space from the different space agencies.

The SFCG is concerned with the effective use and management of those radio frequency bands that are allocated by the Radio Regulations of the ITU to the Space Research, Space Operations, Earth Exploration Satellite, and Meteorological Satellite services.

An important (and relevant for this study) recommendation for Lunar surface is contained in the document REC SFCG 32-2R5, "COMMUNICATION AND POSITIONING, NAVIGATION, AND TIMING FREQUENCY ALLOCATIONS AND SHARING IN THE LUNAR REGION ".

Following these recommendations, it's possible to come up with suitable frequencies to support surface communications on the lunar surface, especially in an early phase of exploration.

The main considerations to be taken into account include:

- To have frequency bands usable on all the surface (e.g. on the "Shielded Zone of the Moon, (SDM), bands above 2GHz should be used.
- To ensure "suitable range", in a first phase of exploration, low frequencies (below 6GHz) are preferred.
- To facilitate standards compliance and interoperability, existing 3GPP bands (or subsets of them) should be used.

Two spectrum blocks listed on REC SFCG 32-2R5 can be considered:

1. 2.5035-2.6550 GHz
2. 3.500-3.800GHz

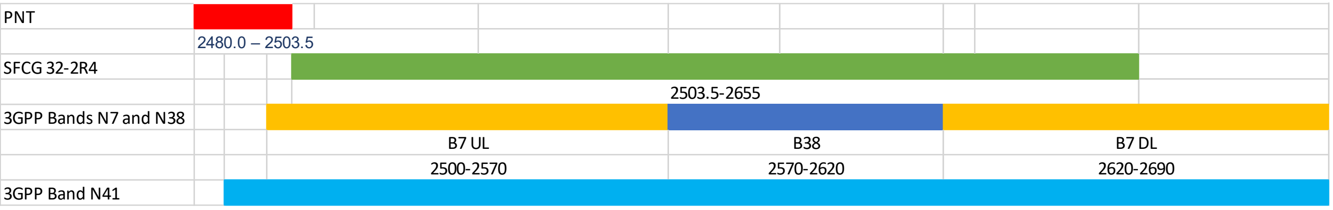
Spectrum around 5GHz defined in REC SFCG 32-R5 is not considered as it overlaps with Wi-Fi spectrum. Further details on those spectrum blocks are described in the following sections.

11.1 2.5035-2.6550 GHz Spectrum

This spectrum block would include part of the following 3GPP bands: N7, N38 and N41.

Figure 57 shows a graphical representation of the spectrum defined in SFCG 32-2R4:

Figure 57. 2.5035 - 2.76550 GHz Spectrum



The green line represents the spectrum defined in REC SFCG 32-2R5; the yellow lines represent the 3GPP spectrum of Band N7; the dark blue line represents the 3GPP spectrum of band N38; the light blue line represents the 3GPP spectrum of band N41.

The usable 3GPP derived bands for lunar operation can therefore be defined as:

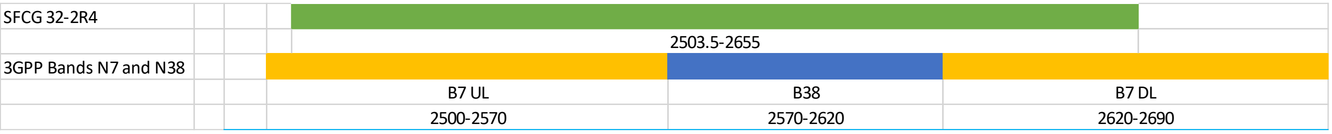
Band N7 (Moon):	2503.5-2570 (UL), 2620-2655 (DL)	(LTE and 5G, FDD, up to 35 MHz)
Band N38 (Moon):	2570-2620 (Uplink and Downlink)	(LTE and 5G, TDD, up to 50 MHz)
Band N41 (Moon):	2503.5-2655 (Uplink and Downlink)	(LTE and 5G, TDD, up to 151.5 MHz)

11.1.1 Coexistence considerations between Band 7 (FDD) and Band 38 (TDD)

In terrestrial applications, coexistence between Band 7 and Band 38 can be problematic.

This is because Band 38 (TDD) is located between UL and DL spectrum of Band 7 (see Figure 58). If both bands were used simultaneously on the lunar surface, care must be taken in properly selecting the appropriate configuration and deployment.

Figure 58: Band 7 and Band 38



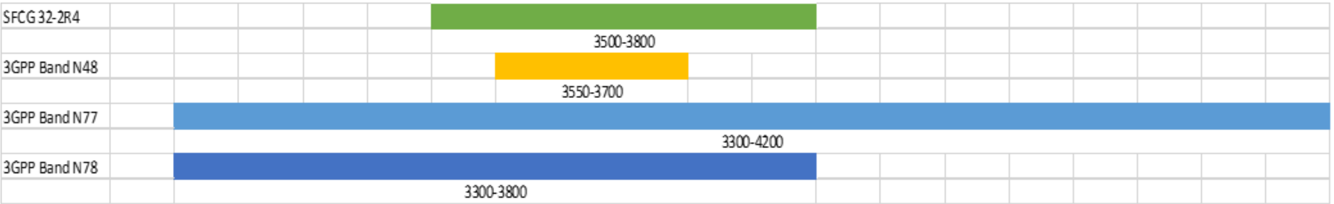
Because of such frequency allocation, B38 TX acts like a blocker for B7 RX and vice versa, both on the NIB (Network in a Box) and the UE (User Equipment) sides.

11.2 3.5000 – 3.8000 GHz Spectrum

This spectrum specification would include part of the following 3GPP bands: N48, N77, N78

Here is a graphical representation of the spectrum defined in SFCG 32-2R4:

Figure 59: 3.5 – 3.8 GHz Spectrum



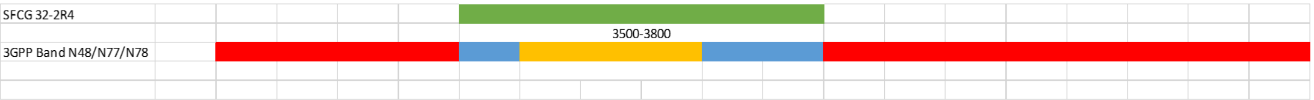
The green line represents the spectrum defined in REC SFCG 32-2R5; the yellow line represents the 3GPP spectrum of Band N48; the light blue line represents the 3GPP spectrum of band N77; the dark blue line represents the 3GPP spectrum of band N78.

The usable 3GPP derived bands for lunar operation can therefore be defined as:

Band N48 (Moon):	3550-3700 (Uplink and downlink)	(LTE and 5G, TDD, up to 150 MHz)
Band N77 (Moon):	3500-3800 (Uplink and Downlink)	(LTE and 5G, TDD, up to 300 MHz)
Band N78 (Moon):	3500-3800 (Uplink and Downlink)	(5G only, TDD, up to 300 MHz)

The usable spectrum is shown in Figure 60.

Figure 60: 3.5-3.8 GHz usable spectrum



	Uplink (UL) BS receive, UE transmit (MHz)	Downlink (DL) BS transmit, UE receive (MHz)	
Band N48:	3550-3700	3550-3700	(150 MHz)
Band N77/N78	3500-3800	3500-3800	(300MHz)
• TDD only			
• N48: no changes in RF Filter specifications required (but not all allocated SFCG band used)			
• N77/78: Requires changes in filter specifications for protecting frequencies outside SFCG Band			

11.3 Conclusions

The available frequencies as defined in Figure 57 and Figure 58 (2.505GHz to 2.655GHz and 3.5GHz to 3.8GHz) appear sufficient for accommodating the requirements and use cases for Artemis V mission.

For future expansion, and depending on the use cases and requirements, adding additional bands could be beneficial, especially considering future capabilities such as multi-band deployments.

The impossibility to use frequencies below 2GHz due to radio astronomy constraints poses limitations on adding a standard 3GPP band. If more spectrum is needed, some possibilities could be:

- Extend the upper bound of the 2.6GHz band to achieve higher FDD bandwidths.
- Use of the spectrum around 5GHz (with high frequency performance penalties in coverage) as defined in SFG 32-2R5, however, coexistence with Wi-Fi needs to be addressed.

12 Security / FIPS considerations

Based on NASA-STD-1006A standard, it is mandated to have FIPS-140 compliant protection for command links, Level 1. Given that some control traffic to certain spacecrafts, e.g., LTV, may be carried over a 3GPP network, this requirement currently applies to the communication of such command traffic over the 3GPP network. In addition, initial NASA requirements and FIPS 140-3 (the most recent FIPS standard) require the use of AES-256 for product certification. Current LTE radio link encryption uses AES-128 and while 5G standards include security enhancements with respect to LTE (e.g., 5G Subscription Concealed Identifier (SUCI)), it still currently uses AES-128 for link encryption.

The above requirements have the following implications from a 3GPP network design and development perspective:

- Requiring AES-256 for 3GPP link encryption will break today's 3GPP standards compliance and will cause significant interoperability and compatibility issues between the network elements (NIB) and UEs.
- Based on certification lab wait lists and schedules, FIPS Cryptographic Module Validation Program (CMVP)[6] certification alone_impacts schedule, not accounting for FIPS-compliant system development costs and schedule impacts.
- FIPS CMVP certification and/or revalidation is per product/product release.

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[6] More information at: https://csrc.nist.gov/projects/cryptographic-algorithm-validation-program

13 Regulatory

Section 11 discussed in detail the spectrum and frequency planning aspects of a 3GPP network deployment following the SFCG 32-2R5 recommendations, including co-existence with other RF spectrum users, e.g., PNT. Further analysis and discussions are for future consideration, including alignment with the NASA Spectrum Office.

In terms of Public Land Mobile Network (PLMN) ID assignations, IT T-REC E.212 already caters for Mobile Country Code (MCC) “999” for use in private networks. It is Nokia’s belief that this PLMN can be used for the initial Artemis mission deployments.

Future network evolution with additional potential network service providers may require additional considerations and selections of other PLMN IDs, e.g., for roaming purposes, but this is beyond of the scope for this study.

14 Schedule Considerations

The objective of this study was to provide a nominal schedule to develop the IOC capability and raise the TRL as needed with potential flight opportunities and terrestrial tests prior to Artemis V. With that in mind, Nokia's approach to building a development schedule is to start from the end i.e., the delivery of flight ready units / system (NIBs, UEs, Antennas, O&M, etc.), and work backwards. In doing so, a schedule should be optimized for the benefits of the Artemis V 3GPP IOC, rather than for individual milestones such as any intermediate DTO's.

A series of important assumptions are needed in building a schedule:

- The Artemis V 3GPP IOC will be managed as one integrated program and optimized for the success of the program. Specifically, NASA will not treat each milestone as a discrete project and potentially optimize for them individually in lieu of what's best for the IOC.
- The chosen communication solution provider should have the typical characteristics of a commercial telecom equipment provider, and as such should have:
    - A deep knowledge of 3GPP.
    - An established technology base in 4G/LTE, 5G/NR, RAN and core network software, cellular localization solution, etc.
    - Proven 3GPP compliance and interoperability.
    - A team of technical experts (development and research) in 3GPP, wireless technologies in general, and E2E communications networks as a whole.
    - An established ecosystem of partners and suppliers.

Although the specifics of any one company will be different from another, these companies should have critical assets and capabilities necessary to leverage as a starting point and ultimately deliver within the Artemis V schedule.

15 Conclusions

Nokia, with the support and guidance of NASA, has conducted a Systems Engineering and Integration (SE&I) study for a 3GPP-based lunar surface network to address the communications and applications needs for future Artemis missions. The study has focused on the development of a plan, with the corresponding technical analysis, for achieving a baseline initial operating capability (IOC) for 3GPP-based extra-vehicular activity (EVA) communications in the Artemis V timeframe. The following high-level conclusions are achieved:

1. 3GPP-based technologies can meet the critical communication requirements for Artemis V and beyond in terms of number of users, data-rates, latency, reliability/criticality and coverage for voice, video and data applications.
2. No other commercially available technology can meet all the above requirements simultaneously.
3. A 3GPP-based network can be engineered, built, and deployed into SWaP-optimized space products and solutions that leverage a commercial, standards compliant, ecosystem rich and proven technology suite that is used by hundreds of millions of people, devices, and machines worldwide.
4. Like in any major technology breakthrough program, there are risks associated to it. We have identified those risks and corresponding mitigations that lead us to believe that the Artemis V 3GPP IOC program can be accomplished successfully.
5. A step-wise integrated approach, with carefully planned and executed DTOs in Artemis III and Artemis IV along with intermediate terrestrial testing is recommended to gradually increase the TRL of the proposed 3GPP network solution, minimize risks and culminate with the Artemis V IOC deployment.
6. From the regulatory aspect, the recommended spectrum from SFCG 32-2R5, exceeds the needs for a 3GPP deployment in Artemis V timeframe. In the future, Nokia could support NASA in discussions with relevant stakeholders (e.g., ITU, FCC, Radio Astronomy community) in navigating regulatory aspects where appropriate.

16 Acknowledgments

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17 List of abbreviations

3GPP	Third Generation Partnership Project
5GC	5G Core Network
AoA	Angle of Arrival
CA	Carrier Aggregation
CC	Component Carrier
CCSDS	Consultative Committee for Space Data Systems
CDR	Critical Design Review
CMVP	Cryptographic Module Validation Program
COTS	Commercial Off-the-shelf
CTE	Coefficient of Thermal Expansion
D2D	Device to Device
DTN	Delay Tolerant Network
DoD	Department of Defense
E2E	End to End
ECC	Error Correction Code
EDU	Engineering Development Unit
EMC	Electromagnetic Compatibility
EMI	Electromagnetic interference
EPC	Evolved Packet Core
EVA	extravehicular activity
FIPS	Federal Information Processing Standards
FIT, FPMH	Failure in Time (failure per million hours)
FPGA	Field programmable gate array
FT	Fault Tolerance
HD	High Definition
HLS	Human Landing System
HW	Hardware

IC	Integrated Circuit
ISS	International Space Station
LTE	Long term evolution
LTV	Lunar Terrain Vehicle
MCC	Mobile Country Code
MNC	Mobile Network Code
MTBF	Mean time between failure
NASA	National Aeronautics and Space Administration
NIB	Network in a Box
NR	New Radio
OCXO	Oven controlled crystal oscillator
Pb	Lead
PCB	Printed Circuit Board
PCBA	Printed Circuit Board Assembly
PDR	Preliminary Design Review
PIM	Passive Intermodulation
PLMN	Public Land Mobile Network
RF	Radio Frequency
ROM	Rough Order of Magnitude
SEE	Single Effect Events
SE&I	Systems Engineering and Integration
Sn	Tin
SnPb	Tin-lead (solder alloy)
SoC	System on Chip
SRAM	Static Random Access Memory
SW	Software
SWaP	Size, weight, and power
TID	Total Ionizing Dose
TIM	Thermal Interface Material

ToA	Time of Arrival
Tvac	Thermal Vacuum
UE	User Equipment

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