Purpose and Notices

Purpose

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Future Lunar Surface Network Study

Final Project Review (Unlimited Data Rights)

2024-03-23

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Agenda

1) Executive Summary
2) Technical Summary
3) Technical Review
    - E2E System Architecture and Engineering
    - Radio Access & Core
    - SW Application Engineering
    - Hardware Engineering
    - Network Performance Evaluation
    - HW & SW Reliability Assurance
    - Spectrum & Frequency Planning
5) Security / FIPS
6) Regulatory
7) Schedule Considerations
8) Conclusions

Executive Summary

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 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.

Technical Summary

E2E Architecture and capabilities

- 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(s) suits.
  - 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.

Technical Summary

SW Applications

- 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.

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Technical Summary

HW Engineering

- 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.

Technical Summary

Network Performance

- Radio Frequency (RF)
  - Predicted SNR and data-rates support communication capabilities 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.
  - Nokia Bell Labs fast propagation modeling tool (or a similarly capable alternative) that takes a digital terrain map as an input and generates predicted path gain for the area Lunar surface communication coverage analysis is essential to support future lunar missions planning.

Technical Summary

HW & SW Reliability

- 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.

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Technical Summary

Spectrum, Security

- 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 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. For example: extending by 10MHz would allow 40MHz in LTE Band N7.
        - 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) 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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Technical review

E2E Systems Architecture

Design Principles

- The 3GPP lunar network should meet the initial operative capability (IOC) requirements (including crit-1 voice) with the minimum complexity while 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 on the lunar surface
- 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 & 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

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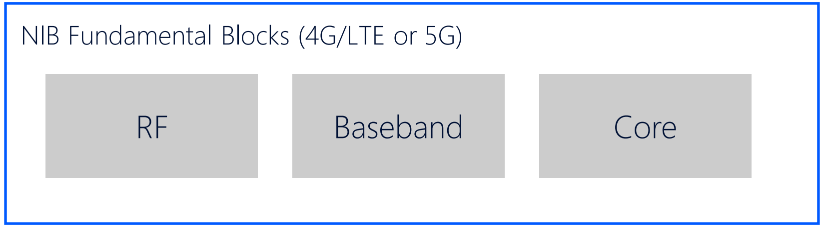
Network in a box (NIB) High-Level View

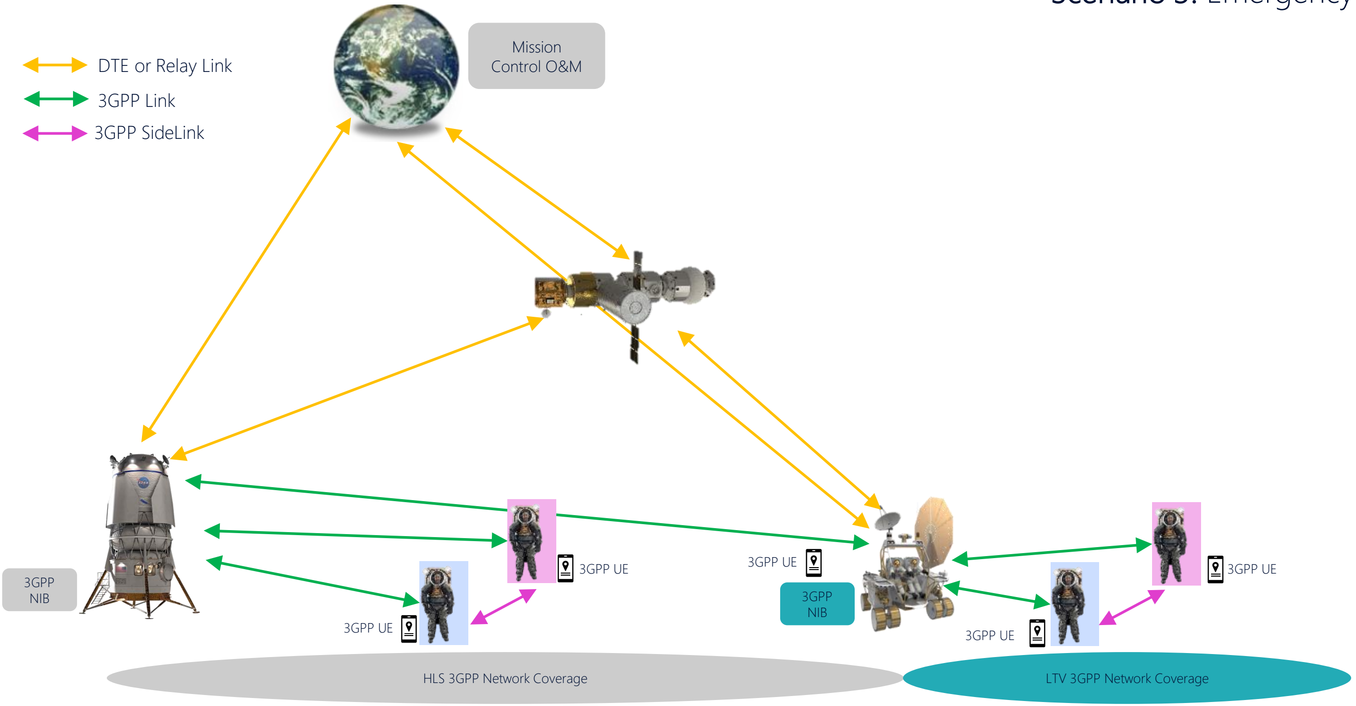
Modular and expandable architecture depending on the deployment scenario



Consolidated System Architecture

<u>Considered Scenarios</u>

Scenario 1: HLS EVA Walk
Scenario 2: LTV EVA
Scenario 3: Emergency Walk-back



Interoperability 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.

Radio Access and Core

Key requirements and assumptions

- Available RF bands according to SFCG 32-2R5.
- Up to 2 astronauts (EVA).
- EVA helmet camera will source one 1080p (FHD) or 4K stream at 30fps using HEVC encoder resulting in 3-12Mbps.
- No more then 4 cameras will be operating simultaneously, either 2 helmet cameras plus two remote EVA (handheld) cameras or 2 helmet cameras plus 2 LTV cameras.
- Single EVA peak data rates
    - DL: < 1Mbps
    - UL single camera: ~13Mbps max
    - UL double camera: ~26Mbps max
- HLS<->LTV peak data rates
    - DL: < 1Mbps
    - UL: ~22Mbps

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Radio Access and Core

Key requirements and assumptions – UL peak data rates NASA vs 3GPP

	NASA requirement	3GPP Rel8 single RF carrier FDD 20MHz	3GPP Rel10 2CC CA FDD (20MHz + 10MHz)	3GPP Rel8 single RF carrier 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

Radio Access and Core

4G/LTE vs 5G/NR

- ✓ Advantages of LTE technology for the Lunar surface communication:
  - ✓ Mature technology
  - ✓ Stable 3GPP specifications
- ✓ Disadvantages of LTE technology for Lunar surface communication:
  - ✓ 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
  - ✓ 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

- ✓ Advantages of NR technology for the Lunar surface communication:
  - ✓ Significantly over provisioned to support increased number of users and future service not yet defined possibly without major changes in the recommended architecture
  - ✓ Additional security features beyond LTE
  - ✓ Supports larger number of radio bands
  - ✓ Current trajectory indicates that SideLink will be commercialized
- ✓ Disadvantages of NR technology for Lunar surface communication:
  - ✓ More complex algorithms in user-plane data processing require more processing power, which may imply increased power consumption wrt to LTE.
  - ✓ Commercial deployments of 5G SA (5G with a standalone mode for the core) are still relatively early in terrestrial operator networks

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.

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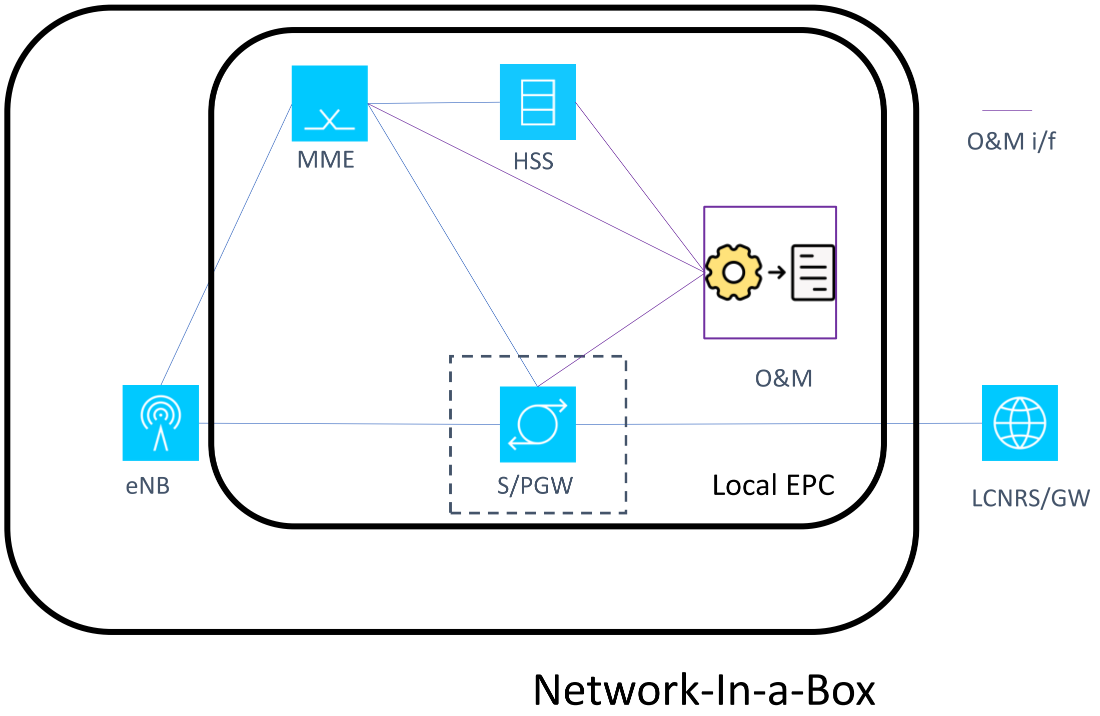
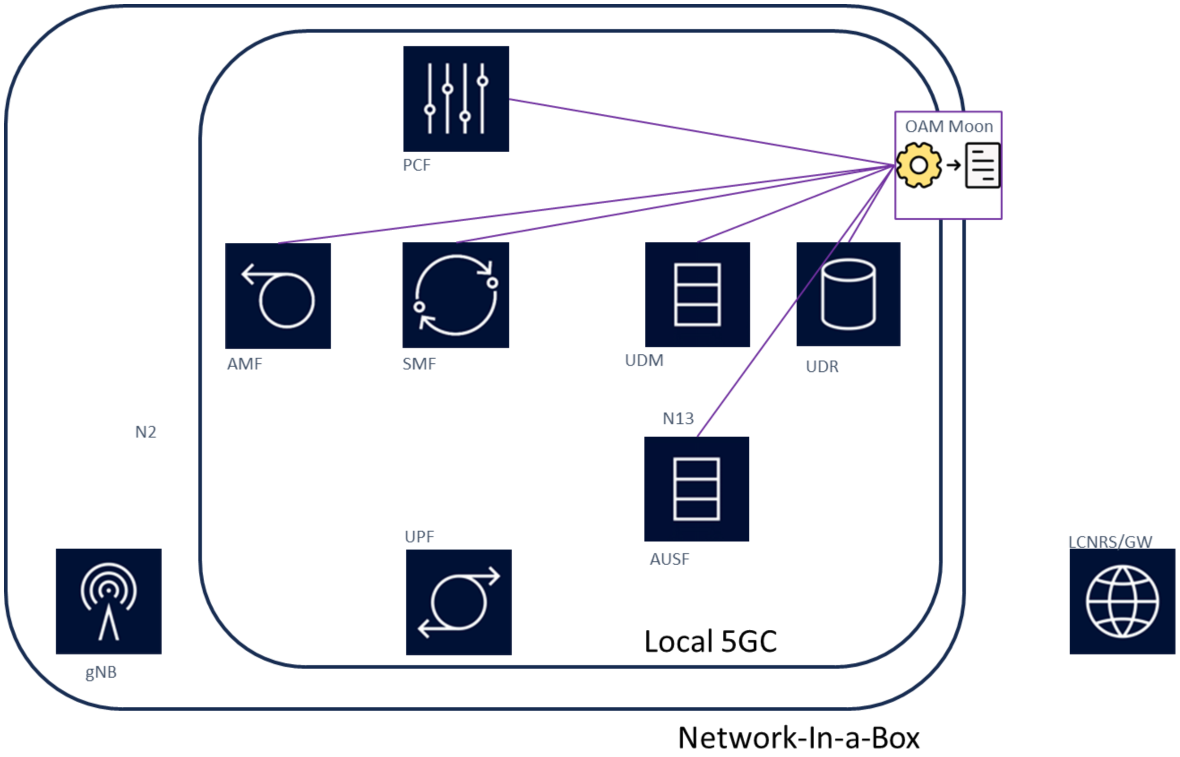
Radio Access and Core

Example of Evolved Packet Core Network for Lunar Network



Radio Access and Core

Example of 5G Core Network for Lunar Network



Radio Access and Core

Conclusions

- 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
- 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.

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Spectrum and Frequency planning

For choosing an appropriate frequency of operation for the 3GPP network on lunar surface, , we referred to the Space Frequency Coordination Group (SFCG) recommendation REC SFCG 32-2R5, "COMMUNICATION AND POSITIONING, NAVIGATION, AND TIMING FREQUENCY ALLOCATIONS AND SHARING IN THE LUNAR REGION"

Considerations:

- 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.

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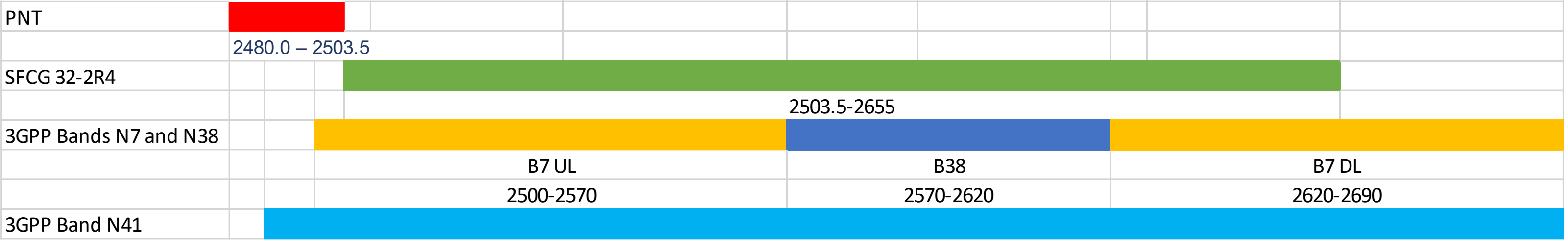
Spectrum and Frequency Planning

Available Spectrum below 6GHz (1/2)

Per SFCG 32-2R5, best candidates are:

1. 2.5035 – 2.6550MHz: N7 (FDD, up to 35MHz BW), N38 (TDD, up to 40MHz BW), N41 (TDD, up to 151.5MHz)
2. 3.5000 – 3.8000: N48 (CBRS US)/77/78 (TDD, up to 100MHz BW)"



Moon Usable:

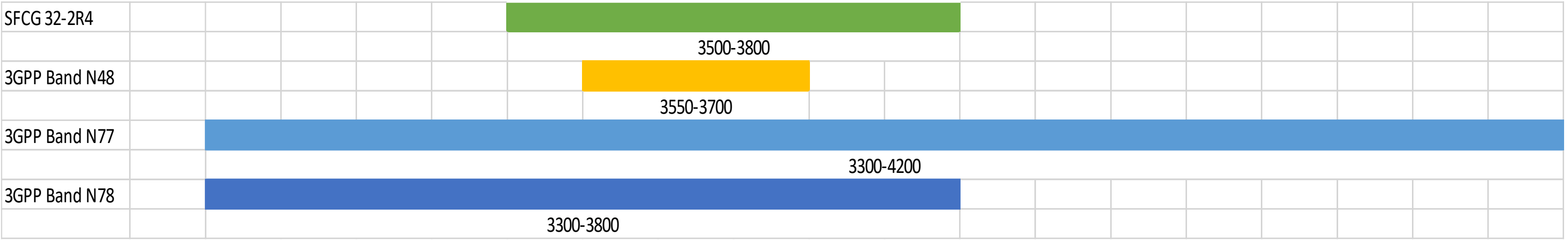
Band N7 (Moon)	2503.5-2570/2620-2655	(LTE and 5G, FDD)
Band N38 (Moon)	2570-2620	(LTE and 5G, TDD)
Band N41 (Moon)	2503.5-2655	(LTE and 5G, TDD)

Spectrum and Frequency Planning

Available Spectrum below 6GHz (2/2)

Per SFCG 32-2R5, best candidates are:

1. 2.5035 – 2.6550MHz: N7 (FDD, up to 35MHz BW), N38 (TDD, up to 40MHz BW), N41 (TDD, up to 151.5MHz)
2. 3.5000 – 3.8000: N48 (CBRS US)/77/78 (TDD, up to 100MHz BW)



Moon Usable

Band N48 (Moon)	3550-3700	(LTE and 5G, TDD)
Band N77 (Moon)	3500-3800	(LTE and 5G, TDD)
Band N78 (Moon)	3500-3800	(5G only, TDD)

Spectrum and Frequency Planning

2.5GHz Bands: Coexistence 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

Essentially B38 TX acts like a blocker for B7 RX and vice versa, both on NIB and UE sides.

Mitigation techniques used in terrestrial networks include:

- Avoid physical co-location (i.e., on the same mast) of B7 BTS and B38 BTS/antennas
- Avoid using both bands on the same UE
- Add guard bands between carriers

SFCG 32-2R4	2503.5-2655		
3GPP Bands N7 and N38	B7 UL	B38	B7 DL
	2500-2570	2570-2620	2620-2690

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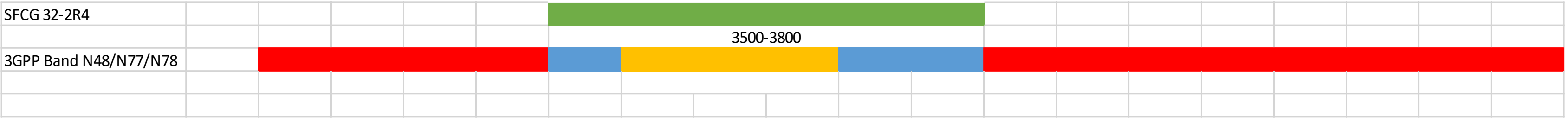
Spectrum and Frequency Planning

3.5 GHz Bands: TDD Only, both LTE and 5G possible



	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			

Spectrum and Frequency Planning

Conclusions

- The available frequencies (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 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.

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Software Applications

Operations and Maintenance (O&M)

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

- real time monitoring of operation of network elements
- handling of telecommands
- software upgrade of telecom protocol stack
- configuration change of RAN and CoreNetwork
- log collection and download

designed for the use case

detailed monitoring of network operation

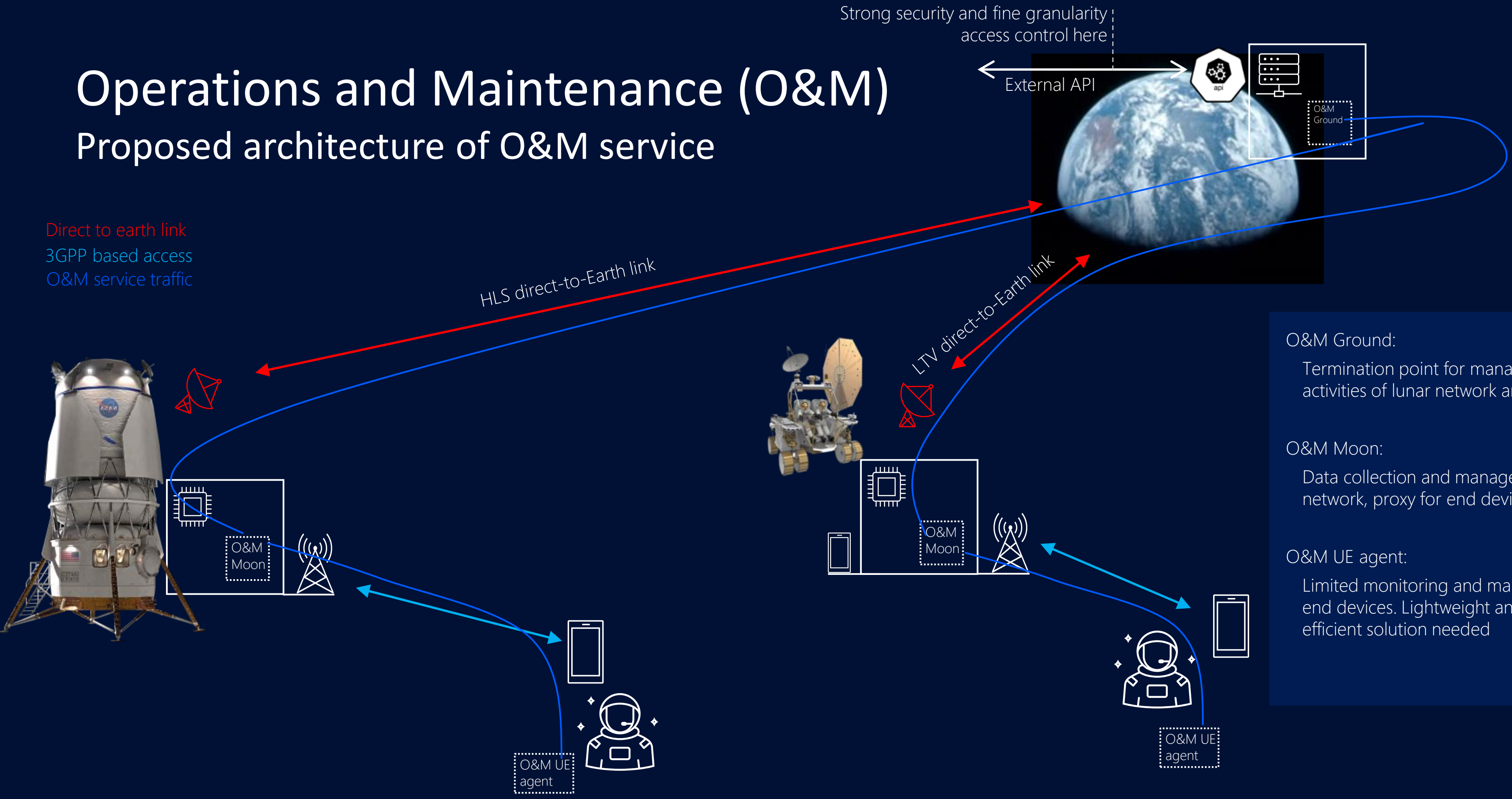
monitoring of UE devices

bandwidth optimized

secure

Operations and Maintenance (O&M)

Proposed architecture of O&M service



O&M Ground:

Termination point for management activities of lunar network and UE devices

O&M Moon:

Data collection and management of lunar network, proxy for end devices O&M.

O&M UE agent:

Limited monitoring and management of end devices. Lightweight and power efficient solution needed

Operations and Maintenance (O&M)

Protocol aspects

- IP based protocol stack would be preferred solution for O&M service communication across DTE links
- Different types of O&M traffic require mapping to different quality of service offered by DTE links
- With E2E O&M security architecture there are no requirements on the security features activated on DTE links

Operations and Maintenance (O&M)

Protocol aspects – O&M traffic types

O&M traffic type	Direction	Bandwidth requirement	Latency requirement	Required reliability	Priority
Real time telemetry	DL	Low, constant stream of data	Real time	Can be temporarily dropped on link congestion	High
Telecommands	UL	Very low, asynchronous events	Low	High reliability required	Critical
TC responses, events and alarms	DL	Low, asynchronous events	Low	High reliability required	Critical
Log streaming / download	DL	Medium, on demand when log collection requested	Background	Reliability required; app level reliability is enough	Medium
Configuration upload	UL	Low, on demand when configuration change requested	Med	Reliability required; app level reliability is enough	High
Software upload / file upload	UL	High, on demand, rare scenario.	Background	Reliability required; app level reliability is enough	Low

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Operations and Maintenance (O&M)

Conclusions

- O&M should be custom designed for the use case
  - Specific requirements of managing small scale telecom network
  - At remote and inaccessible location
  - Providing critical communication services
- High delay, limited data-rates and potentially constrained satellite links availability should all be factored in the O&M framework design
- O&M designed and implemented with strong security features in place
- All elements of the communication system (NIBs, UE and O&M) need to be developed in conjunction with each other and can not be developed in isolation of each other without the risk of significant issues or large integration efforts

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Voice Application – Basic requirements

- Dynamic, and potentially large # of Earth participants
- Control: typical conference control for Earth participants: add/drop, mute/unmute

- Small, known, fixed set of Moon participants
- Local sub-conferences of network-connected subgroups
- Seamless attach/detach of local sub-conferences

Voice Application – Other requirements

- Implementation
  - (Modular/Pluggable) support for multiple codecs
  - Power efficient
- Non-functional
  - Availability
  - Security
- Miscellaneous
  - Local voice archive
  - Inter-working with other conferencing services (if needed)

Contrasting Earth and Moon Networking

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

Earth

Moon

- Availability of general dynamic internetworking and routing protocols

- Some internetworking protocols connecting Moon entities
- Environment/Mobility can trigger network reconfiguration and packet losses

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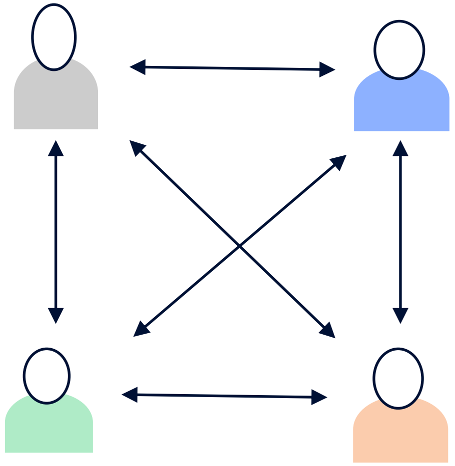
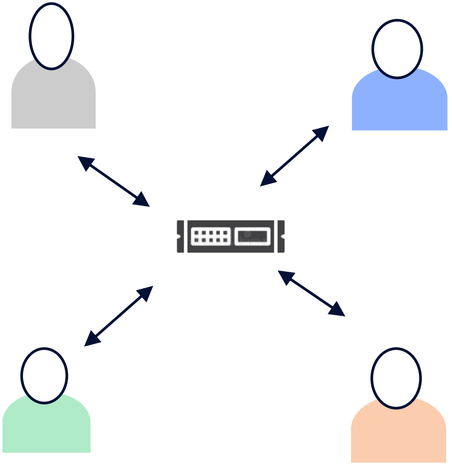
Voice Conferencing Architecture (Examples)

Server-based

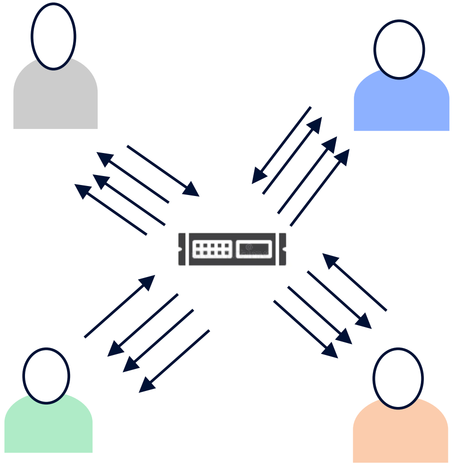
Peer to Peer (P2P)



Multipoint Control Unit (MCU)



Selective Forwarding Unit (SFU)



Design Considerations

Earth

Earth-Moon Links

Moon

Earth

- Network characteristics of general Internet
- No power/processing constraints
- Sophisticated control

Earth-Moon Links

- Lower bandwidth
- High latency
- Higher packet losses

Moon

- Environment/Mobility triggered packet losses
- Low congestion for voice
- Power/processing constraints

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Voice Solutions

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 to be addressed is 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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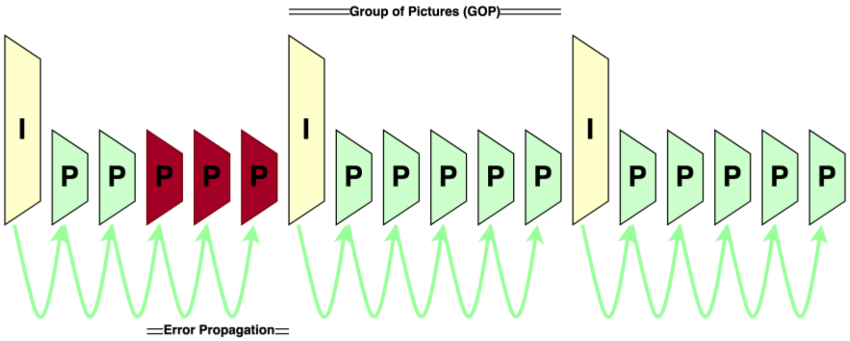
Video Architecture

Key highlights

- A Video Gateway function is highly desirable to bridge between the LTE Networks and LunaNet DTE/DTN links
- Additional recommendations on the structure and transport of Video Bitstreams potentially can improve error resilience and contribute to limiting latency
- Don't rule out H.264. It still performs well above 3-4 Mbit (1080p30) and has significant complexity advantages.



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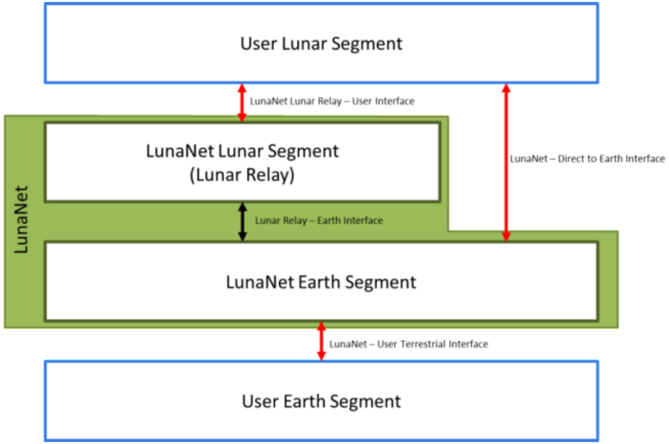
Video Architecture

Gateway Recommendation

- The User Lunar Segment is a bridge between the 3GPP network and LunaNet
- Gateway functionality is implicit in this picture
  - A Gateway can aggregate multiple video streams and relay from the Moon to the Earth
  - Streams can be re-encapsulated and optionally transcoded for the Direct to Earth link
  - With server functionality, Streams can further be locally stored/saved for introduction to DTN relay opportunistically or saved for later archival and return on physical media



Ref: LunaNet Interoperability Specification ESC-LCRNS-SPEC-0015, Version 4

H.264 vs H.265 comparison

4k 2160p at 4Mbit

H.264 vs H.265 comparison

4k 2160p at 6Mbit

Hardware Engineering

NIB HW Engineering

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

- Different use cases for lunar network compared to commercial terrestrial networks

Commercial terrestrial Networks requirements
Multiple cells for coverage of a sizable geographical area
Extremely high throughput for large number of concurrent users
Cost optimized
Distributed, multiple HW "boxes"

↔

Exploration lunar network requirements
Limited number of simultaneous users with high throughput
Limited geographical coverage
Integrated, SWAP optimized

NIB HW Engineering

Key Blocks investigation

Current typical RAN implementation consists of:

- Servers (x86 based)
- Custom HW boards (L2/L1/Radio)
- CPU (x86/ARM), ASICs/SoCs (custom design), FPGA
- Radio components (amplifiers, etc.)

Current RAN implementations are optimized for:

- Multiple cells, thousands of users, very high throughput
- Cost

- Lunar deployment approach:
  - Network elements integrated in one single enclosure, expandable (“Network in a Box”)
  - Environmental requirements (mechanical, thermal, outgassing properties, radiation tolerance)

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NIB HW Engineering

Use of Rad-hard components on NIB

- Moving from a SoC-optimized component to a RadHard solution implies a higher power consumption figure
  - PCBA “real estate” should not be significantly impacted using rad-hard components.
- Power dissipation increase would impact NIB mass/weight significantly

NIB HW Engineering

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.

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UE Engineering

Device-to-Device (D2D) options

SideLink (3GPP Rel.16 and up)

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

3GPP C-V2X

Pros:

- Data rates are high (in new revisions)
- Demand of high reliability coming from vehicle 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 auto industry
- C-V2X operates in what is known as the ITS band in 5.9 GHz spectrum (requires separate chipset)

UE Engineering

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.
  - We recommended that a detailed characterization of their performance be started as soon as possible. This characterization is critical to understand the limitations of the commercial modems for 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.
  - While 5G SideLink support in commercial cellular modems is open at the moment, discussions with a leading manufacturer in the US presents a promising outlook for both prototype availability and future functionality support in commercial modems.
  - We recommend establishing demonstrations and testing of the technical as early as possible to evaluate the current state of the technology.
  - Existing UHF solutions in EVA suits are recommended to be maintained in the first Artemis missions to provide a back-up communications link.

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Network Performance

RF Performance Evaluation

Propagation Model Design

- Need fast propagation model that includes variable terrain:
    - Empirical models: fast, but neglect terrain variations on the moon
    - Heuristic knife-edge models under-predict effect of hills & boulders
    - Numerical parabolic equation/integral equation solvers are too slow
- We've developed a fast, analytic model methodology.
- Calibration of the new propagation model by performing an extensive measurement campaign with Vodafone in Lunar-like terrain on Fuerteventura, Canary Islands.

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RF Performance Evaluation

Key Simulation Assumptions

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)

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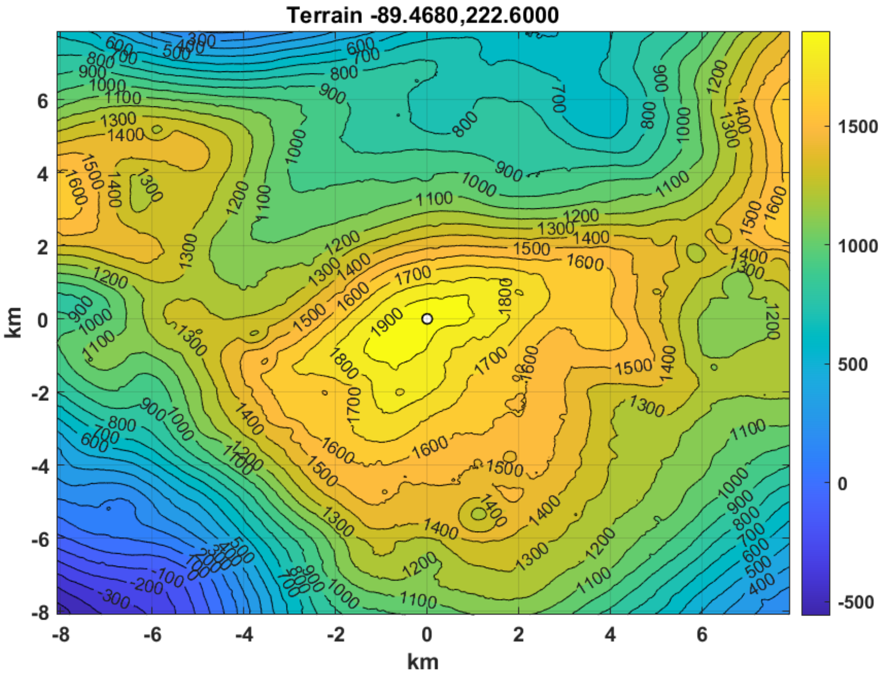
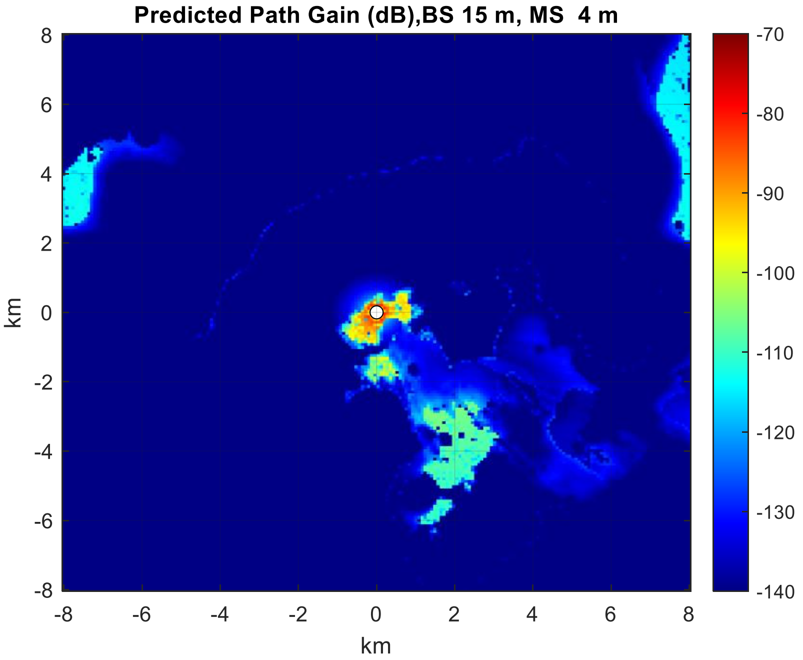
RF Performance Evaluation

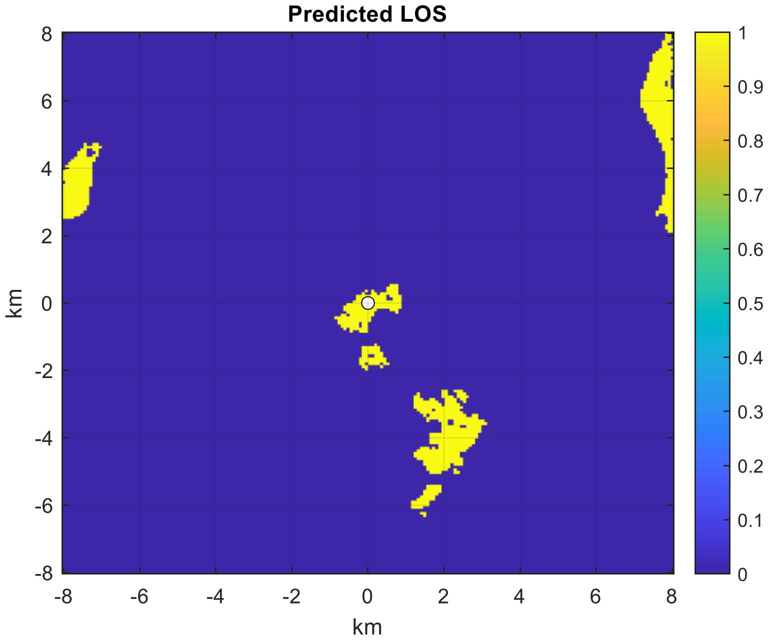
Terrain profile around CR1 site



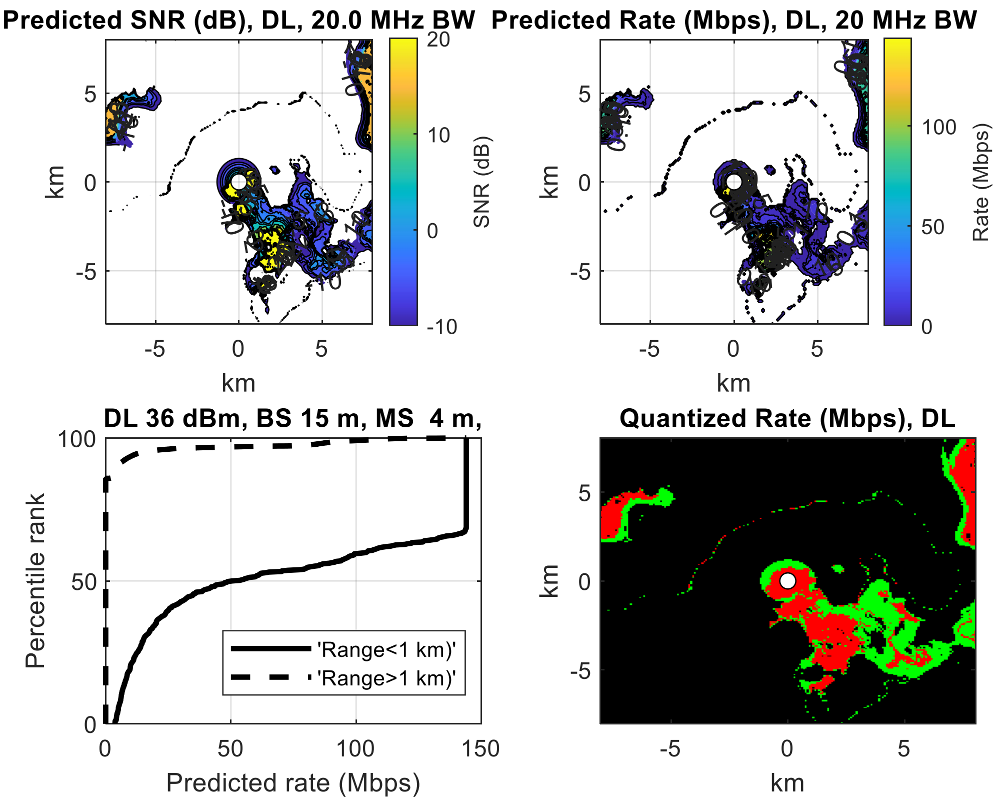
RF Performance Evaluation

Path gain and predicted LOS for 15m HLS, 4m LTV





DL SNR and Rate for 15 m HLS, 4 m LTV

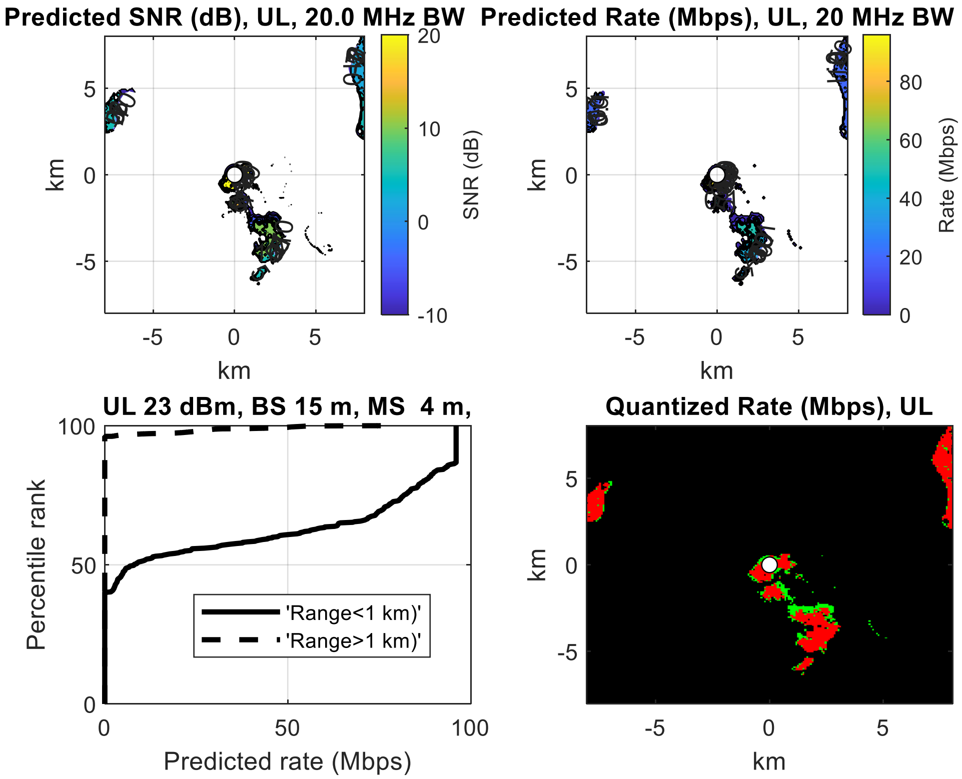


Red: >10 Mbps (Video)

Green: >200 kbps,<10 Mbps (Voice)

Black <200 kbps

UL SNR and Rate for 15 m HLS, 4 m LTV

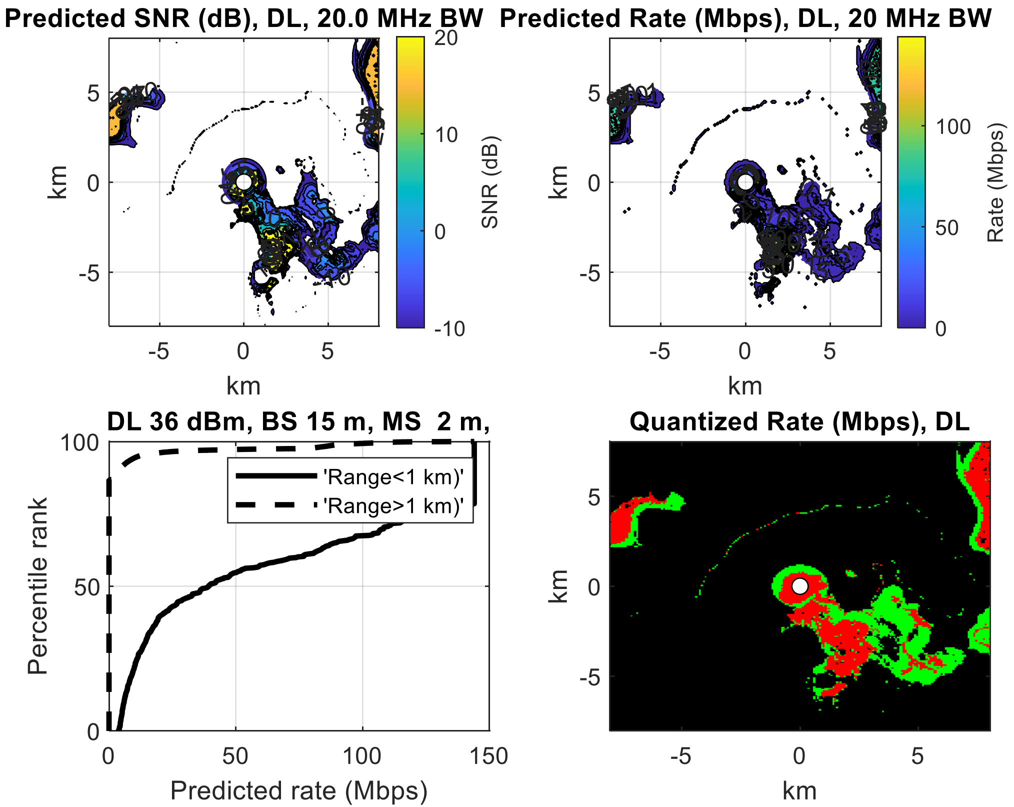


Red: >10 Mbps (Video)

Green: >200 kbps,<10 Mbps (Voice)

Black <200 kbps

DL SNR and Rate for 15 m HLS, 2 m Astronaut



Red: >10 Mbps (Video)

Green: >200 kbps,<10 Mbps (Voice)

Black <200 kbps

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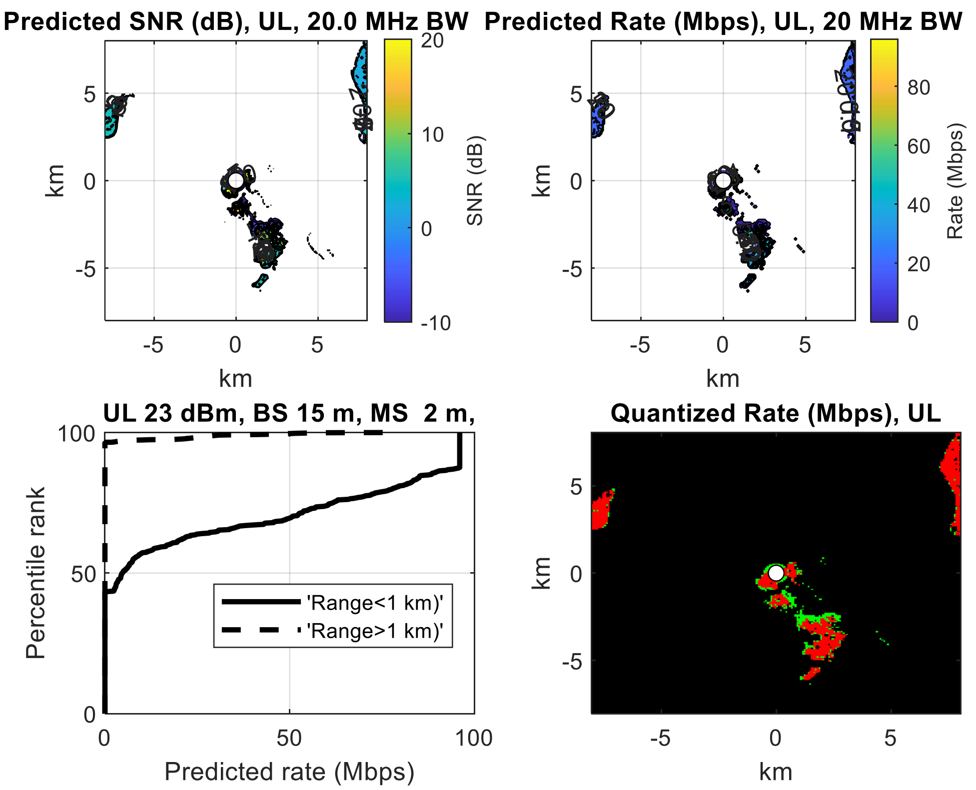
UL SNR and Rate for 15 m HLS, 2 m Astronaut



Red: >10 Mbps (Video)

Green: >200 kbps,<10 Mbps (Voice)

Black <200 kbps

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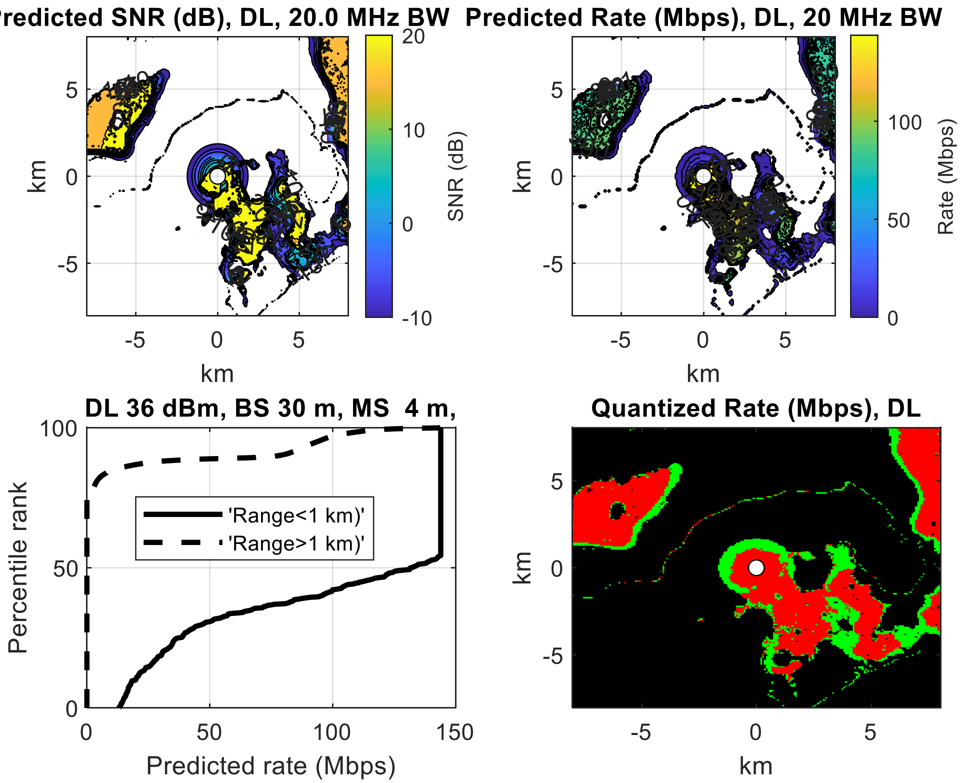
DL SNR and Rate for 30 m HLS, 4 m LTV



Red: >10 Mbps (Video)

Green: >200 kbps,<10 Mbps (Voice)

Black <200 kbps

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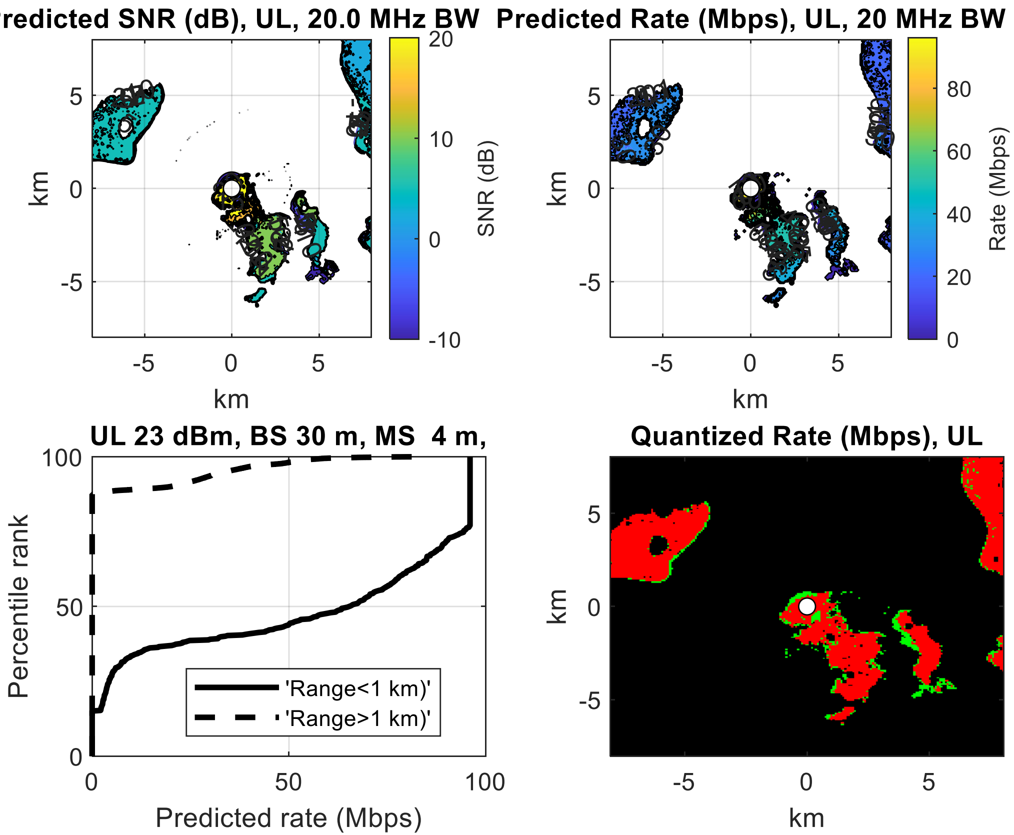
UL SNR and Rate for 30 m HLS, 4 m LTV

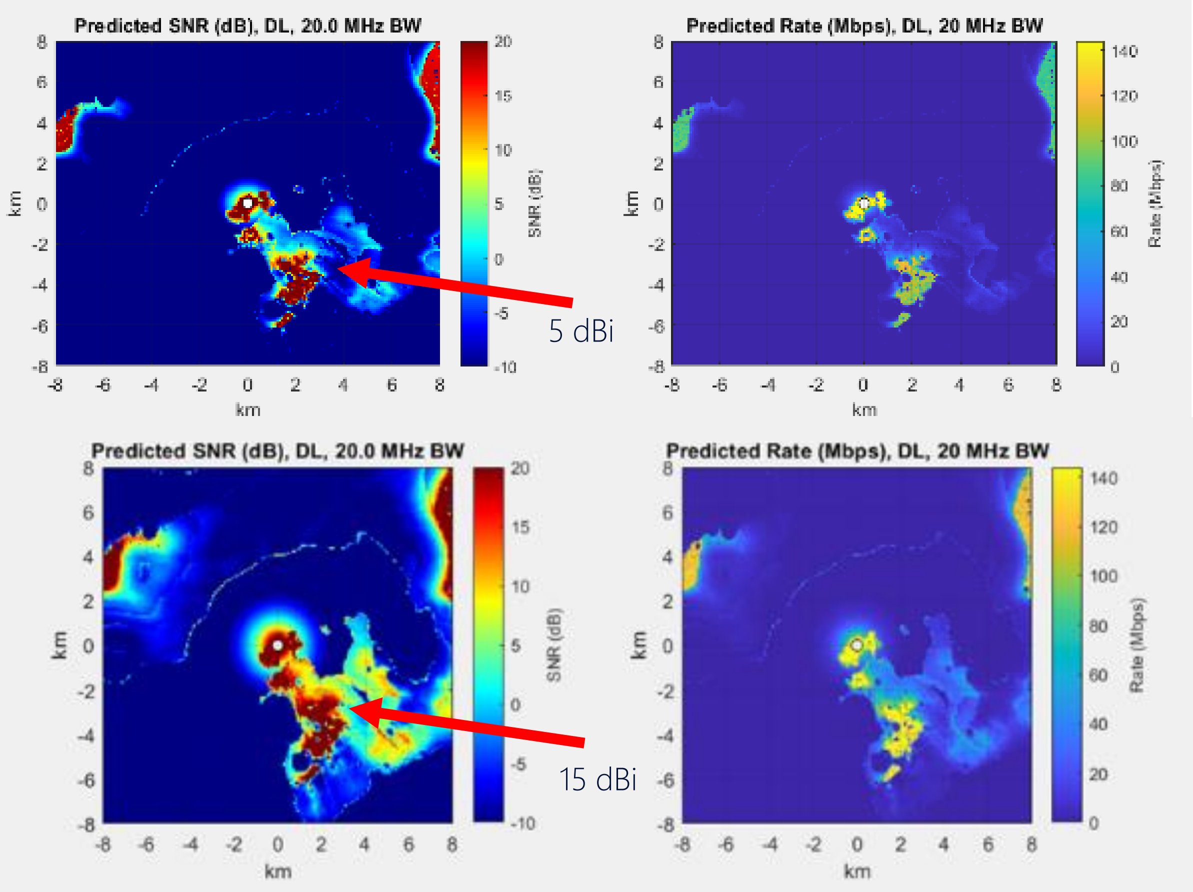


Red: >10 Mbps (Video)

Green: >200 kbps,<10 Mbps (Voice)

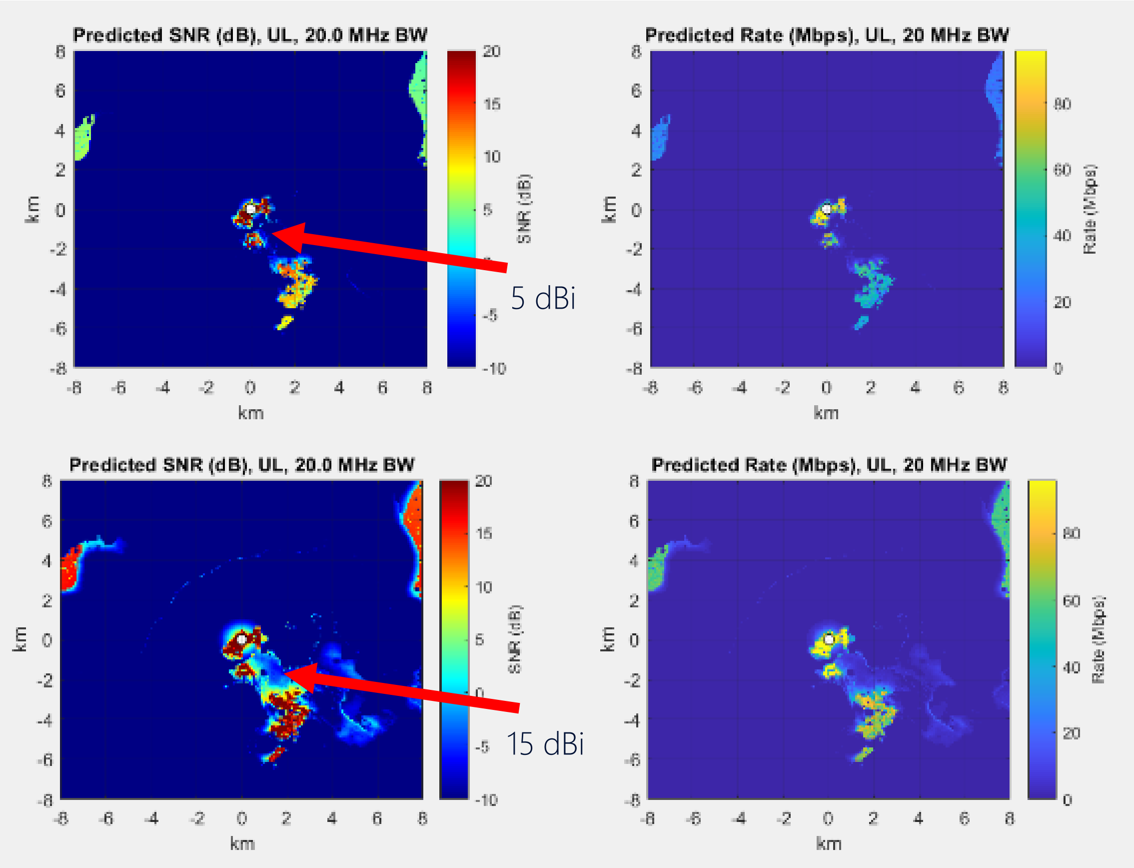
Black <200 kbps

DL SNR and Data-Rate for 15m Lander, 2m Astronaut, Directional Antenna



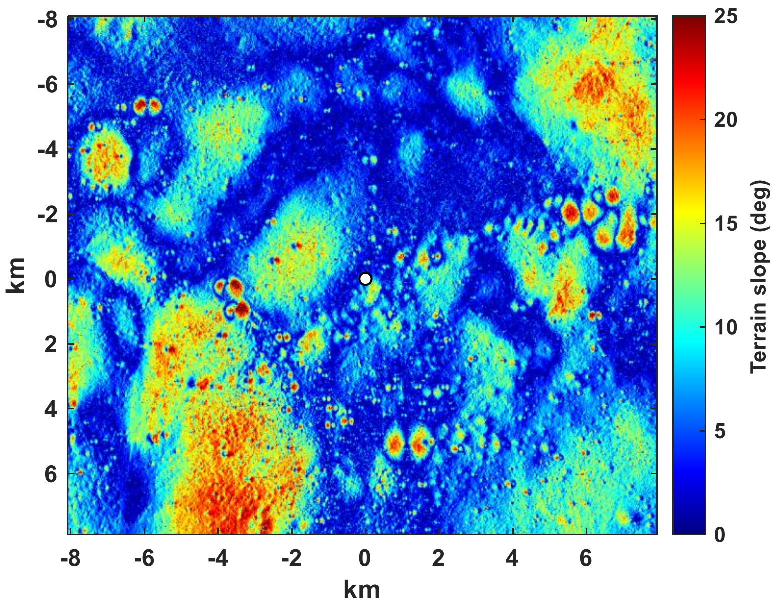
Improved coverage and data rates with 15 dBi antenna

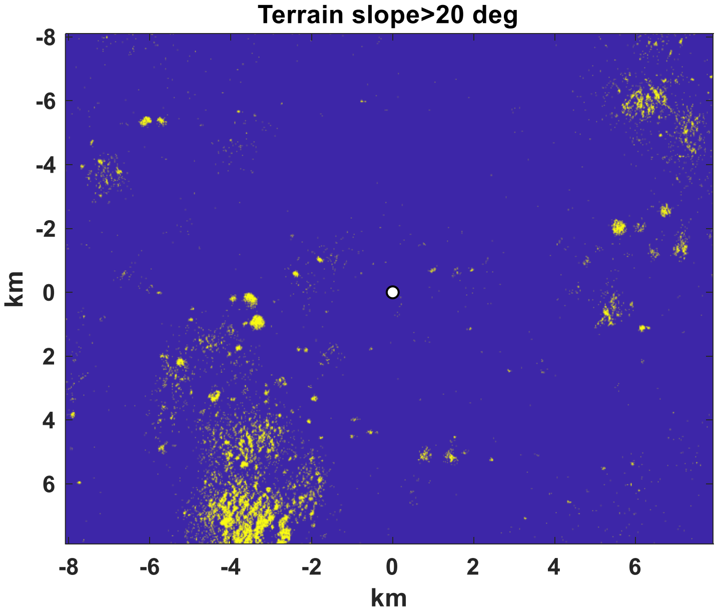
UL SNR and Data-Rate for 15m Lander, 2m Astronaut, Directional Antenna



Improved coverage and data rates with 15 dBi antenna

Terrain Slope Analysis: No-go zones (>20 deg slope)





Quantized terrain slope: >20deg in yellow

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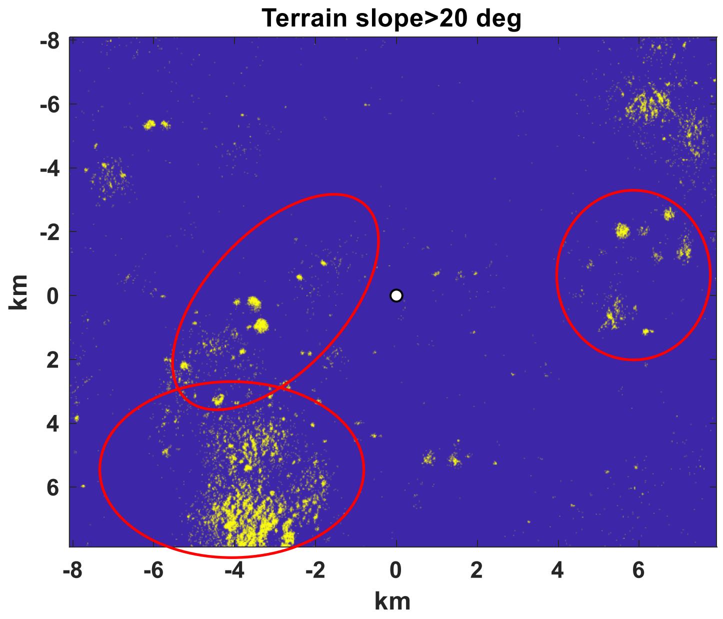
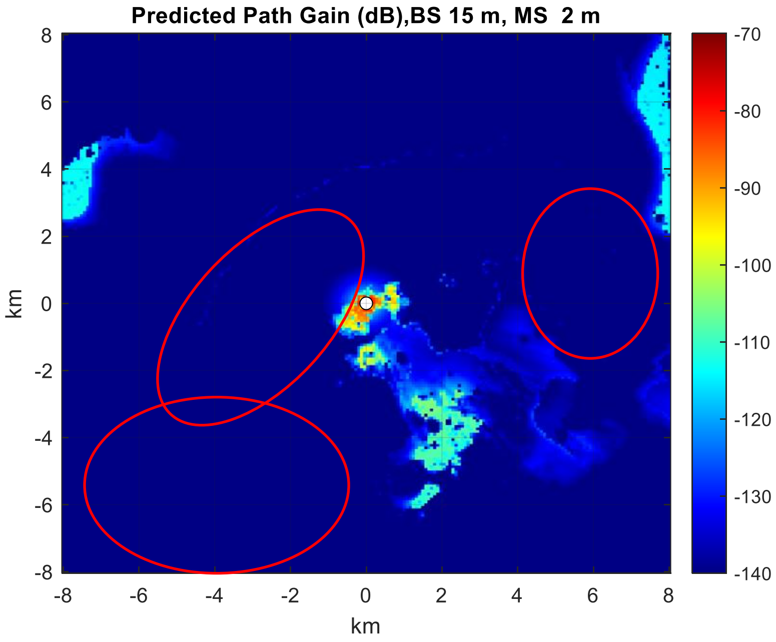
Terrain Slope Analysis: Side by Side comparison with Path Gain





Circled areas correspond to no-go zones and with low-path gain areas where traverses are not possible

RF Performance Evaluation

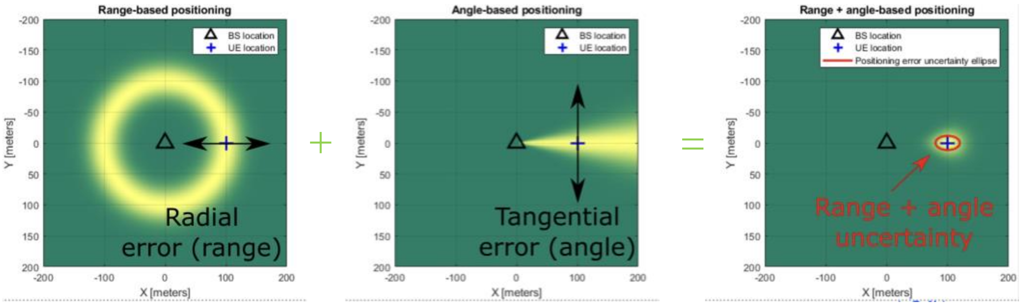
Conclusions

- Lunar surface communication coverage analysis is essential to support future lunar missions 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, either an 4m high LTV or a 2m dismounted astronaut.
- Key impairment limiting 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 predicting communication performance, such as SNR and rate follow directly. This report details the coverage estimate methodology and key results.
- <u>Predicted SNR and data-rates support communication capabilities to 10 km</u>. 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.

Localization Evaluation

Exploring options for radio-based 2D positioning with a single base station

- **Motivation**: In addition to communication, determining the accurate location of mobile objects (e.g., unmanned lunar vehicle) in real time is a key enabling technology.
- **Goal**: Explore positioning technologies based on existing radio communication protocols (4G LTE / 5G NR/ IEEE 802.11 WiFi) suitable for the lunar mission.
- **Key assumptions**: UEs integrated to Astronaut's EVA suits, and there is a single NIB infrastructure node at the HLS.



- **Range estimation**: Distance can be estimated by measuring the time it takes a transmitted signal to reach a receiver. More bandwidth gives higher accuracy. Standards-based options:
  - Timing advance (4G, 5G): Used to synchronize BS and UEs. Affected by bounded but unknown timing advance error (TAE).
  - Round-trip time (5G, Wi-Fi): Requires uplink and downlink measurements, not affected by TAE.
- **Angle estimation**: Estimate by measuring phase of received signal across array elements. More elements give higher accuracy.

Localization Evaluation

Simulation Assumptions

- We built a simulator to predict the positioning performance using waveforms corresponding to:
  - WiFi (FTM)
  - LTE (TA)
  - 5G NR (multi-RTT)
- Assumptions:
  - SCR2b landing location (lat=-89.4876; lon=-138.2528) from Dmitry Chizhik based on *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
- Evaluated root mean-square (RMS) error of 2D position estimate versus distance from the lander (SCR2b landing location).

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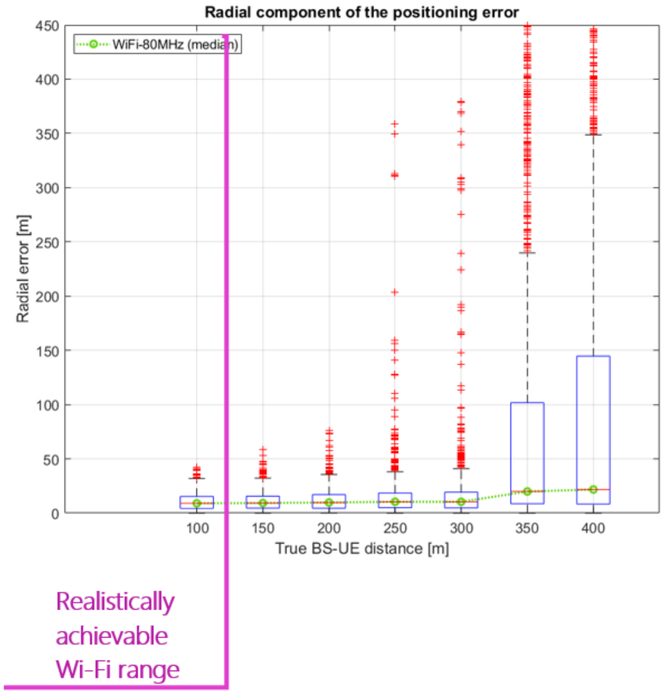
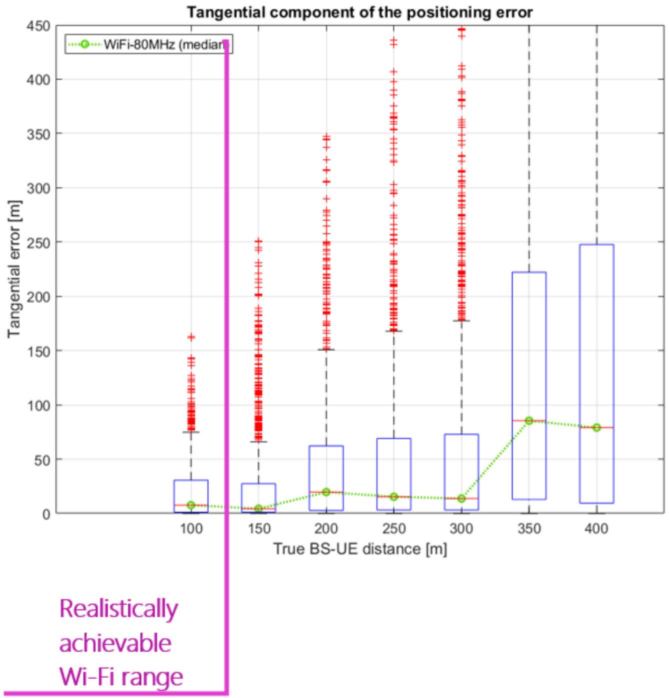
Localization Evaluation

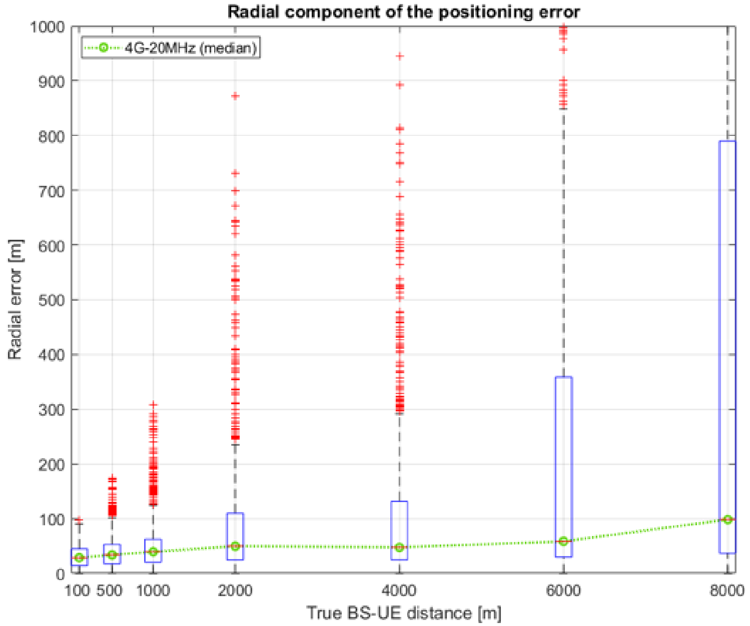
Simulation Results: Radial and tangential positioning error vs. true distance for Wi-Fi (B = 80 MHz)

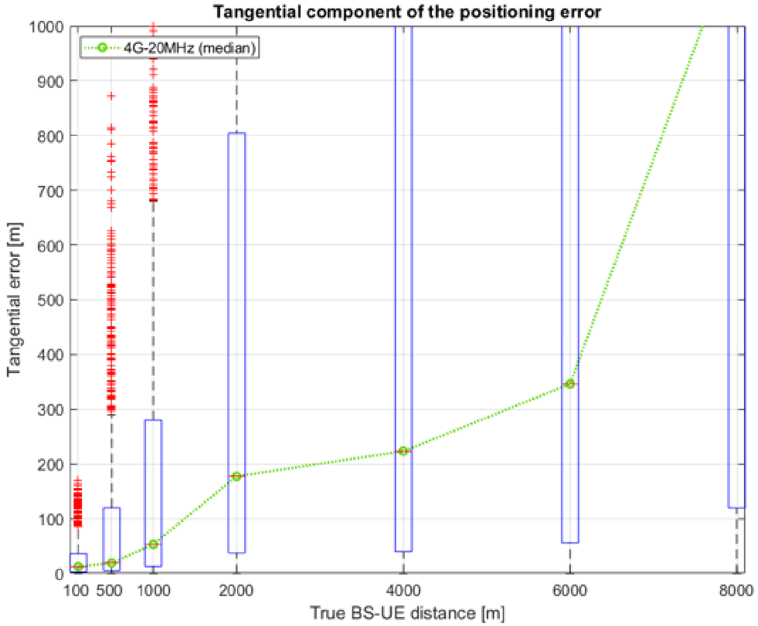




Localization Evaluation

Simulation Results: Radial and tangential positioning error vs. true distance for LTE (B = 20 MHz)





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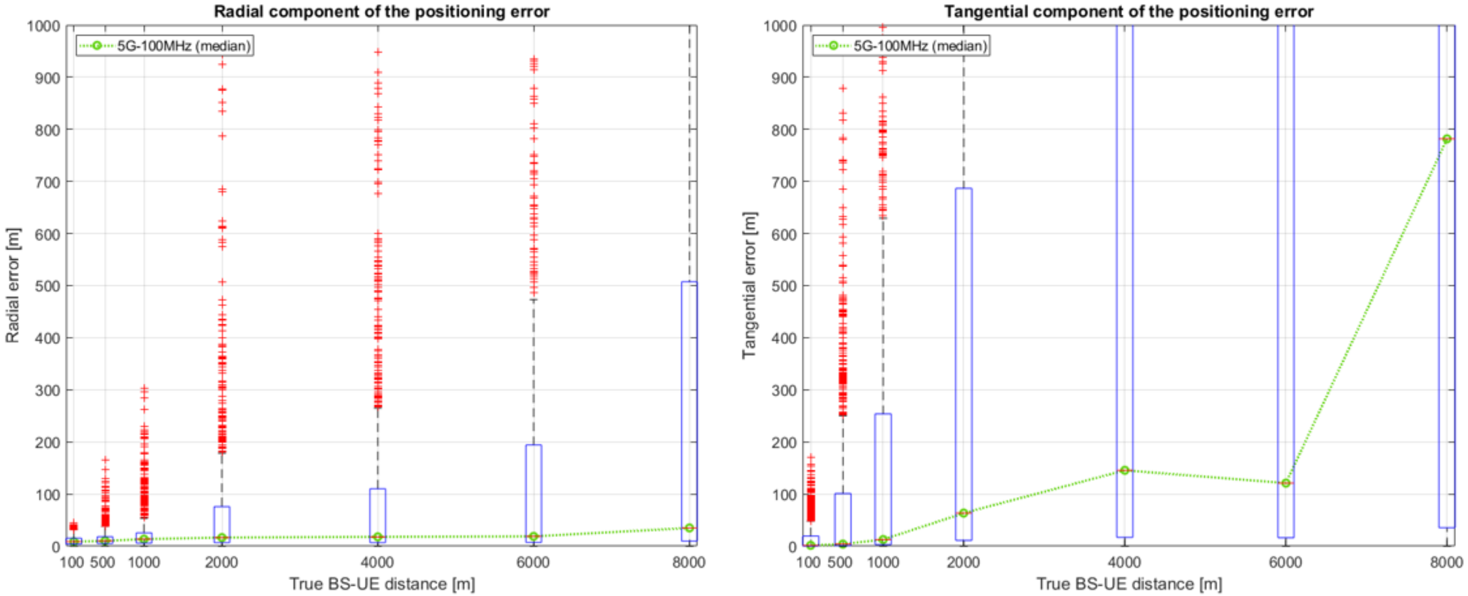
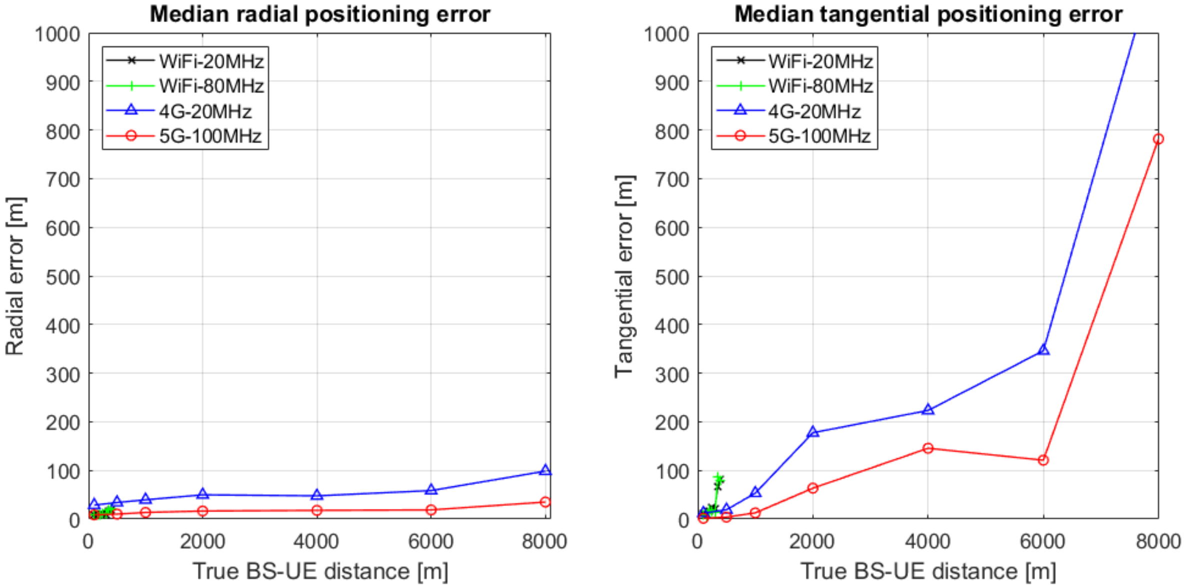
Localization Evaluation

Simulation Results: Radial and tangential positioning error vs. true distance for 5G (B = 100 MHz)



Localization Evaluation

Simulation Results: 4G/LTE vs 5G/NR



Reliability Assurance

Hardware Reliability

Key Highlights

- Ground up design recommended with changes to telecom industry standard design, procurement, parts assurance/control practices, and assembly practices
- Use of existing Space Application supply chain ecosystem strongly recommended to help alleviate some of the issues associated with bullet above
- Procure space qualified parts to the extent possible.
    - Additional upscreening and/or selective testing may be required
    - SWAP impacts possible due to transition from COTS components
    - Components not on approved lists may need to be refinished
- Redundancy to be implemented for NIB and UE in order to meet fault tolerance requirements

Software Reliability

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. Telecom industry norm for verifying SW is more relaxed

→ Complying with all these requirements is costly, impacts development time and it can become prohibitive or impossible to achieve in some instances (e.g., in low-level firmware for SoCs or FPGAs or vast baseline/legacy code for 3GPP components)

Software Reliability

Key Highlights

- 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.

Security, Regulatory and Schedule

Security / FIPS

- 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.
- 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 list and schedules, FIPS Cryptographic Module Validation Program (CMVP) 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.

Regulatory

- Details have been discussed of the spectrum and frequency planning aspects of a 3GPP network deployment following 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 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.

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Schedule Considerations

- The Artemis V 3GPP IOC will be managed as one integrated program 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
  - An established ecosystem of partners and suppliers

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Conclusions

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 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.

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Acknowledgements

Nokia would like to thank the NASA, APL and JPL teams that participated in this SE&I study. The continuous support, push, encouragement, information exchange and open discussions made it possible to successfully complete this activity.

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