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# Envisioned Lunar Surface Communications Using 3GPP Cellular and Wi-Fi Technologies

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**Abstract**

Under NASA's Artemis Program, NASA plans to collaborate with commercial and international partners to establish a long-term human and robotic presence on the Moon. Critical lunar infrastructure includes having a robust surface wireless communications and navigation network to be developed over time by many organizations, public and private. NASA's Space Technology Mission Directorate (STMD) has envisioned a lunar surface future that includes the use of 3rd Generation Partnership Project (3GPP) cellular and 802.11 Wi-Fi technologies. NASA and Nokia Bell Labs are studying and validating the benefits and trade-offs of using 3GPP 4G and 5G technologies originally developed for use here on Earth, and how 3GPP technologies and 802.11 Wi-Fi technologies can be integrated to provide a robust and resilient end-to-end network architecture and solution design. Furthermore, as the 3GPP organization defines future 6G capabilities, NASA wants to understand how that could enhance lunar science and exploration missions and commercial endeavours to provide even more advanced, scalable and high-performance connectivity solutions. The vision is to provide human and robotic missions on the Moon with similar communications and navigation capabilities to what mobile users have on Earth, while adapting these technologies into space-hardened solutions that withstand the environmental and operational challenges of the lunar surface. STMD's Tipping Point program seeks industry-developed space technologies that can both foster commercial space capabilities and benefit future NASA missions. Via Tipping Point, Nokia Bell Labs will demonstrate the use of 4G / LTE on the lunar surface on the Intuitive Machines IM-2 mission. This will be followed with a technology demonstration with astronauts on the Artemis III lunar landing. This paper provides an overview of NASA's current and planned future work on using 3GPP and 802.11 Wi-Fi on the Moon.
**Keywords: Cellular, 3GPP, 5G, 4G, LTE**

## 1. Introduction

The NASA Artemis campaign will return humanity to the Moon, establish a long-term presence there, and open more of the lunar surface to exploration than ever before. The expected rapid growth of lunar activity requires robust and resilient communication, navigation, and networking capabilities for crew safety, the command and control of spacecraft, the return of science data, and the precise manoeuvring of assets both in space and on the lunar surface. These goals are also intended to develop new technologies and capabilities supporting exploration of Mars through the Moon-to-Mars (M2M) architecture. NASA's M2M Objectives [1] include Lunar Infrastructure Objective 2 for communications: "Develop a lunar surface, orbital, and Moon-to-Earth communications architecture capable of scaling to support long term science, exploration, and industrial needs".

With this infrastructure need in mind, STMD led a NASA cross-program cross-directorate 3rd Generation Partnership Project (3GPP) Cellular Working Group from 2021 to 2023 that focused on how NASA could use 3GPP technologies in space [2]. Critical inputs to the group came from 3GPP work that was already on-going within NASA, including:

- Analysis, simulations, and field tests by Nokia Bell Labs for the STMD 4G / LTE Tipping Point Demonstration on Intuitive Machines' IM-2 mission to launch no earlier than February 2025.
- International standardization work in 3GPP for use in space led by NASA Johnson Space Center in the Consultative Committee for Space Data Systems (CCSDS).

- Lunar surface 3GPP analysis and simulations led by NASA Glenn Research Center [3].
- 3GPP analysis in the context of the Artemis program led by NASA's Extravehicular Activity and Human Surface Mobility (EHP) Program.
- A System Engineering and Integration (SE&I) Study performed by Nokia Bell Labs to identify a suitable architecture and high-level system design to support future lunar missions, specifically aimed at the mission requirements and operational needs of the Artemis V mission and beyond.

NASA's 3GPP Cellular Working Group recommended that NASA baseline 3GPP technologies for planetary surface communications, including the Moon as well as Mars. For human missions to Mars, a robust surface network is of even greater necessity given the need for increased self-sufficiency and resilience because of the Earth-to-Mars communication delays (up to 21 minutes one-way) and blackouts (up to 22 days) [4]. While the 3GPP working group recommendation was being made, EHP was working in parallel to baseline 3GPP and Wi-Fi 5 for the future Lunar Terrain Vehicle (similar to the rover used during Apollo missions) for Artemis-V. EHP was also successful in securing support inside NASA for a technology demonstration of 3GPP cellular technologies on the Artemis-III mission, the first crewed lunar landing for NASA since Apollo 17. This technology demonstration will integrate cellular technologies from Nokia Bell Labs into the next-generation Axiom Extravehicular Mobility Unit (AxEMU) spacesuits developed by Axiom Space.

## 2. First Cellular Network on the Moon

In October 2020, STMD awarded Nokia a contract to deploy the first 4G/LTE cellular network on the lunar surface as part of STMD's Tipping Point initiative, which fosters the development of commercial space technologies to benefit future space missions [5]. To realize this demonstration, Nokia partnered with two leading commercial space companies to deploy and test its 4G/LTE based Lunar Surface Communications System (LSCS): Intuitive Machines, who would provide the flight and landing platform through one of their Nova-C lunar lander missions; and Lunar Outpost, whose Mobile Autonomous Prospecting Platform (MAPP) rover, also manifested for an Intuitive Machines flight, would operate as a mobile user on the lunar surface. The LSCS demonstration will launch in February 2025 as part of the second Intuitive Machines mission to the Moon, IM-2, after their inaugural mission, IM-1, which was the first successful commercial lunar landing on February 22, 2024. The mission will land on the south pole of the Moon in early March 2025 and will operate for up to two weeks during lunar daylight.

The key objective is to demonstrate that terrestrial cellular technologies that connect billions of smartphones on Earth can meet the critical communication needs of future missions to the Moon and Mars. To accomplish this, Nokia, powered by the research of Nokia Bell Labs, completely reconceptualized the 4G/LTE cellular network, engineering a highly resilient, size, weight and power (SWAP) optimized system capable of operating autonomously under the harsh environmental conditions of the Moon [6]. The main components of this solution are depicted in Figure 1 and described below.

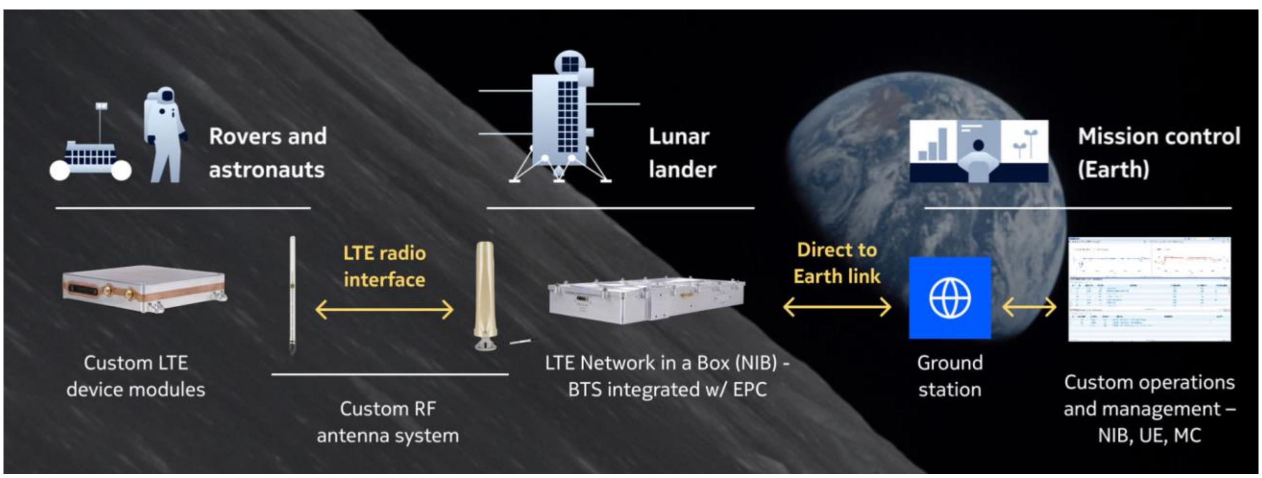


*Figure 1: Nokia Bell Labs Lunar Surface Communications System (LSCS)*

1) **Network in a Box (NIB)**: a dual hardware-redundant network solution that includes both 4G/LTE Base Transceiver Station (BTS) and Evolved Packet Core (EPC) functionalities, integrated onto Intuitive Machines' Nova-C class lander, together with custom-designed Radio Frequency (RF) antennas.
2) **Device module**: a custom 4G/LTE modem, optimized for extended coverage, integrated onto Lunar Outpost's Mobile Autonomous Prospecting Platform (MAPP) Rover along with another set of RF antennas.
3) **Operations and Maintenance (O&M):** a mission control software suite optimized for operation over the long-latency, low data-rate and lossy direct-to-Earth (DTE) radio links that will allow remote operators on Earth to monitor and operate the 4G/LTE network elements deployed on the Moon.

Upon landing on the Moon, the LSCS's NIB will be powered up and autonomously configure itself to establish a wireless network that will provide high-speed low-latency communications capabilities on the lunar surface. This network will enable reliable transmission of high-definition video streaming, command-and-control and telemetry data for the MAPP Rover.

As the rover traverses the lunar landscape, it will continue to use the 4G/LTE network to connect back to Nova-C in two main scenarios: short-range, on the order of 200-300m, and long-range up to 2km from the lander, which will be critical in evaluating the performance of the network over the variable terrain of the Moon.

Comprehensive data from the LSCS subsystems will be transmitted in real-time down to Nokia's Ground Station to monitor the system health and performance. Furthermore, network key performance indicators (KPIs) will be collected and eventually used to calibrate Nokia Bell Labs lunar propagation models [7] that will be fundamental for future missions planning.

Through a different STMD Tipping Point award, one of the goals of the IM-2 mission will be to also deploy the Micro-Nova Hopper spacecraft developed by Intuitive Machines to test new sensor instruments that could help identify and map resources on the Moon, like water ice. The Micro-Nova Hopper also integrates a LSCS device module which will enable all data collected to be transmitted over the 4G/LTE network to the Nova-C lander, even as the Micro-Nova Hopper descends into permanently shaded craters.

## 3. Integrating Cellular Technologies into Next-Generation Spacesuits

Going beyond the IM-2 mission, our aim is to further advance the 3GPP communication technologies and validate them in more complex and crewed missions. With that objective in mind, a new Communication Demonstration Test Objective (DTO) for the Artemis-III mission was commissioned by NASA in August 2024 to Axiom Space and Nokia. The primary intent of this DTO is to aid in developing NASA's future 3GPP-based communication systems for lunar surface assets that will inform potential future upgrades and requirements for Extra Vehicular Activities (EVA) systems, Human Landing System (HLS) landers, lunar rovers, and lunar payloads.

The baseline Axiom's EVA (AxEVA) system architecture utilizes ultrahigh frequency (UHF) radio for transmitting voice and limited telemetry data and WiFi for transmitting video over very short distances of the order of 100-300m at most. This Communication DTO will demonstrate additional capabilities for the AxEVA system architecture through implementation of a 3GPP-compliant solution using Nokia's 4G/LTE LSCS technology to achieve much higher data rates for simultaneous transmission of mission critical voice, data, telemetry and high-definition video over extended long distances of 2km and more.

Axiom and Nokia's strategy for quickly and efficiently executing this communication DTO is to leverage the space-hardened hardware and software assets developed by Nokia for STMD's Tipping Point program described in Section 2. The Communication DTO will integrate a modified version of this technology into a human rated EVA system and an HLS lander. Some key planned design and development work on the 4G/LTE LSCS solution include:

1) Modification of the existing NIB and device module hardware and software to operate in 3GPP Band 7, in line with the latest spectrum recommendations described in Space Frequency Coordination Group Recommendation SFCG 32-2R5 "Communication and Positioning, Navigation, and Timing Frequency Allocations and Sharing in the Lunar Region" [8].
2) Design and development of new RF antennas for the device modules and NIB to operate in the new frequency band and suitably adapted for mounting onto EVA suits and the HLS.
3) Modification and development of new O&M software modules.
4) Integration of the modified LSCS 4G/LTE solution components to AxEMU spacesuits [9], the HLS lander and mission control centers.
5) Support mission concept of operations (ConOps) and DTO activities on the lunar surface.
6) Support post communication DTO analysis.

The Communication DTO includes the following key objectives to form the basis for determination of success. The minimum success criteria, as well as reach goals to assess enhanced capability, are defined for each objective.

*Table 1: Communication DTO Objectives*

| Objective | Success Criteria (threshold) | Reach Goals |
|---|---|---|
| DTO EVAs | Demonstrate DTO on a single EVA | Demonstrate DTO on 2 or more EVAs |
| DTO Execution Time | Two (2) 1-hour activity windows during EVA, for a total of 2 hours per EVA | Four (4) 1-hour activity windows during EVA, for a total of 4 hours per EVA |
| Data Transmitted | 45 minutes 720p HD video per activity window not including startup, checkout, and shutdown | 45 minutes 1080p HD video per activity window not including startup, checkout, and shutdown |
| Data Transmit Distance | 2 km or max planned EVA distance, whichever is shorter | 2.5 km, 3 km, 4 km to demonstrate enhanced performance |
| Real-time Telemetry and Network Performance Data Capture | Telemetry data from NIB and device module is stored in local disks and analyzed post-mission | Telemetry data from NIB and device module is received in near real-time in Mission Control Center |
| DTO Data Transfer Analysis | Post mission data transfer performance analysis | Near realtime data transfer performance analysis, complete before next activity window |

The primary objective of the DTO is to demonstrate transfer of High Definition (HD) video over Nokia's 4G/LTE solution at a minimum distance of 2km for the AxEMU on the Artemis-III mission. NASA currently envisions having two crew members perform EVAs during the Artemis-III mission, so the baseline solution includes performing the Communication DTO for both AxEMU spacesuits. The AxEMU will nominally communicate suit telemetry and audio over UHF Radio, and high-definition video over Wi-Fi. Both capabilities will be retained for the AxEMU during the DTO EVAs.

The activities associated with the Communication DTO will be incorporated into the Artemis-III EVA plan by NASA, in coordination with the proposed DTO objectives. It is expected that when the crew initiates a communication DTO performance period (activity window), they would continue normal exploration and science activities in parallel to executing the DTO. The first DTO activity window is expected to occur while close to the HLS vehicle to ensure the equipment is functioning properly while at short range, then at longer ranges up to the maximum planned distance of 2km or greater later in the EVA. Additional periods of operation that exceed the baseline will be performed whenever possible throughout the EVA activities to evaluate various terrain interference impacts as well as measure the long-range data throughput performance.

## 4. 3GPP System Engineering and Integration (SE&I) Study

In the summer of 2023, NASA's Space Communications and Navigation (SCaN) program-funded a Systems Engineering and Integration (SE&I) study with Nokia Bell Labs, in conjunction with EHP at NASA's Johnson Space Center. The goal of the study was to assess the feasibility of using 3GPP technologies as the primary means of mission critical communication for astronauts in the Artemis V timeframe. Whereas Artemis III and Artemis IV feature two crew members traversing up to 2km on foot from the HLS, Artemis V plans to add a Lunar Terrain Vehicle (LTV) rover which the astronauts can use to travel up to 10km from their HLS. Under the guidelines of the study, each EVA suit was assumed to produce crew member audio, suit telemetry, and helmet camera video at full high definition (FHD) or ultra-high definition (UHD) resolution. Suits were also allowed to relay video from a handheld camera routed through a Wi-Fi access point on the suit. Both the HLS and the LTV could serve as communication terminals with access to orbital or direct-to-Earth (DTE) links to send voice, video, and telemetry data back to Earth, to send mission control center (MCC) audio from Earth to the two crew members, and to serve as hubs through which crew members could talk to each other. In addition to potentially hosting crew members, the LTV was assumed to be fitted with two FHD-UHD cameras of its own. Both the HLS and LTV were assumed to contain Wi-Fi access points (WAPs) according to a baseline Artemis communication architecture, and the EVA suits were assumed to include Wi-Fi radios that could act in either the client or soft access point (AP) modes.

The SE&I study was designed to determine if a 3GPP-based system would be able to perform the same critical audio and telemetry tasks as the legacy UHF Space to Space Communication System (SSCS) while extending the audio range to the full 10km EVA extent and supporting transport of non-critical video data beyond Wi-Fi ranges up to the 10km limit. The time-division multiple access (TDMA)-based SSCS controls access to a shared medium by assigning dedicated transmit slots to each of only five users; this has the advantage of decentralization, wherein any one SSCS radio that can close a link with the others can communicate with them without the need for a central hub or controller. As this ability is considered a key EVA communication service, any 3GPP-based solution should also be able to close a link with other EVA suits when in range and line of sight of them, even if a 3GPP base station is not currently in that suit's view.

In addition to the above service requirements, a variety of NASA standards were highlighted for evaluation, including reliability, software assurance, and hardware quality assurance; fault tolerance requirements and lunar environmental specifications, including radiation tolerance levels, were also specified.

The SE&I study produced a detailed, government-only report as well as an unlimited rights, public report. The latter is available at [10], along with a summary presentation detailing the findings at a high level [11]. At a high level, the critical conclusions were as follows:

1) Among commercial technologies, 3GPP systems were identified as uniquely capable of providing all the required services simultaneously.
2) A feasible path to development of space hardened and size, weight, and power (SWaP)-optimized 3GPP solutions for Artemis was outlined; integrated "network in a box" (NIB) solutions were suggested for HLS/LTV (combining 3GPP core and Radio Area Network/RAN functionality), with user equipment (UE) radios integrated into suits and, optionally, the LTV.
3) A progressive set of demonstrations leveraging Artemis flight opportunities was suggested prior to use in critical applications in the Artemis-V timeframe, due to the technical risk of the development effort.

In addition, the SE&I study evaluated the suitability of early lunar 3GPP deployments for position, navigation, and timing (PNT) applications, suggested voice and video application architectures, explored HLS, LTV, and suit antenna designs, and analysed communication coverage in a representative area of the lunar south pole on the connection ridge between the Shackleton and de Gerlache craters.

## 5. Vision for the Future

Our vision is that future space exploration, long-term human presence on the Moon and on Mars, and the developing space economy are only possible with advanced communication, networking and computing solutions. Leveraging the most advanced communication solutions for this future leads us to believe that 3GPP based technologies will provide the reliable, high-performance and cost-effective mission critical communications needed for future missions. That includes crewed missions beyond Artemis-III as well as uncrewed robotic, science and technology missions. A lunar surface wireless infrastructure built on 3GPP and WiFi meets the Lunar Infrastructure Objective 2 of the Moon to Mars Objectives to "Develop a lunar surface, orbital, and Moon-to-Earth communications architecture capable of scaling to support long term science, exploration, and industrial needs". We believe strongly that NASA (and other governmental space agencies and space industry at large) should make maximum use of commercial communications and navigation technologies designed for use on Earth whenever possible. Doing so would provide advance communications and navigation technologies at significantly reduced costs compared to custom NASA systems while providing superior performance and ecosystem interoperability. An initial network, with a single base station installed in a HLS, would be sufficient to support the initial mission requirements of a single Artemis mission. When the HLS leaves, however, so does the network. In the not-too-distant future, more and more missions will be conducted on the Moon. These missions will establish a permanent human presence, build out human habitats, conduct resource mining and drilling activities, provide surface transportation systems and advance our knowledge through science and technology missions. These sensors and robots should be wirelessly connected just like Internet of Things (IoT) devices here on Earth. It will be more efficient and economically viable to have a permanent lunar surface communication network built out over time to benefit and support all missions.

One can imagine that future CLPS missions carry and deploy base stations (network in a box equipment) to provide permanent surface coverage to nearby users with increasing coverage over time. Furthermore, as 3GPP technologies improve on Earth, NASA could transition those performance improvements to the Moon. A key example is the emerging development of 3GPP non-terrestrial-networking (NTN) on Earth; eventually NTN technologies could also be used from orbiting lunar communication satellites to provide extensive coverage in more remote exploration areas of the lunar surface that do not yet have a high-capacity surface communication network and to connect multiple surface exploration areas. Finaly, when there are multiple organizations operating on the Moon, one can imagine one or more 3GPP commercial service providers selling hardware and cellular services to meet the surface communications needs.

## 6. Conclusions

OnEarth, we use Wi-Fi for very short range and 3GPP-based cellular technologies for mission-critical short to long range high-capacity wireless communications. The joint use of 3GPP and Wi-Fi will allow NASA and the space industry to leverage the decades of expertise and experience of engineers designing some of the most sophisticated wireless communications systems ever developed. The standards-based 3GPP technologies will continue to advance their performance, develop additional features and capabilities, and scale for future network and traffic demands and thereby allow the ability to add users and infrastructure over time as needed. NASA and the space industry can and should take advantage of the large investment made in commercial telecommunications development around the world and the experience gained from thousands of deployments and operations in global commercial service provider networks, enterprise and industrial networks, public safety and mission critical deployments. Space qualified 3GPP cellular technologies will provide new ways to support high-speed ultra-reliable, low-latency mobile communications on the lunar surface and beyond.

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