5G New Radio and Non-Terrestrial Networks: Reaching New Heights

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As the need for limitless connectivity surges, non-terrestrial networks (NTN) will play a central role in fifth generation (5G) and beyond communications. The 3rd Generation Partnership Project (3GPP) defines NTN as networks, or segments of networks, using an airborne or space-borne vehicle as a relay node or base station. Satellites are examples of space-borne vehicles, while High Altitude Platform Stations (HAPS) are examples of airborne vehicles. An NTN-enhanced cellular network supplements a conventional terrestrial cellular network. This article provides an overview of NTN-enhanced cellular networks with a particular focus on satellite-mobile direct communications. First, we review satellite system classifications such as Geostationary Orbit (GEO), Medium Earth Orbit (MEO), and Low Earth Orbit (LEO), spectrum usage, and key challenges of satellite communications. We then summarize recent 3GPP activities in NTN. In addition, we describe our recent proof-of-concept system involving a satellite channel emulator and modification of the 5G New Radio (NR) protocol stack to handle the challenge of long round-trip time – demonstrating the feasibility of NTN and the adoption of NTN-enhanced cellular networks in 5G and beyond communications. Finally, we highlight the main open issues and future research challenges of NTN-enhanced cellular networks.

***Index Terms*—Non-terrestrial networks (NTN), 3GPP, Proof-of-concept.**

I. Introduction

SATELLITES – and other airborne vehicles – have the potential to radically transform cellular communications in the fifth generation (5G) era and beyond, since they can provide ubiquitous coverage to mobile devices, especially when those mobile devices are located beyond the coverage area of conventional terrestrial base stations (BSs). To realize this potential, the 3rd Generation Partnership Project (3GPP) envisions supplementing the coverage of conventional terrestrial networks (TN) with non-terrestrial networks (NTN) in the design of 5G New Radio (NR). NTN refers to networks, or segments of networks, using satellites, airborne or spaceborne vehicles for transmission including High Altitude Platform Station (HAPS). In this article, we focus on NTN based on satellites including Geostationary-Earth-Orbit (GEO), Medium-Earth-Orbit (MEO), and Low-Earth-Orbit (LEO). Such satellite-assisted cellular networks are empowered by several factors, including proper deployment of a network of space-borne/airborne devices and innovative communication protocols, which will be introduced in this article.

The 3GPP is playing a key role in the development of solutions for 5G NR to support NTN. Since NTN can provide reliable and wide-coverage connections, it enables unique use cases differentiated from – and supplemental to – a conventional TN. During natural disasters including earthquakes, hurricanes, and wildfires, the airborne NTN BS is unaffected by power outages, enabling it to maintain connectivity (it can establish connections with multiple NTN gateways, including gateways outside of a disaster area). NTN can also provide cellular connectivity to locations where the deployment of BSs is technically or financially challenging, including mountains, rural areas, or seas. In addition, NTN can enable rapid, cost-effective nationwide coverage when deploying a next-generation cellular network. For instance, nationwide coverage can be achieved by deploying only a few tens or hundreds of Low-Earth-Orbit (LEO) satellites; the resulting network can supplement a subsequently-deployed TN (the deployment of that TN would be relatively time-consuming and costly). The Iridium system, which operates at an altitude of 780 km, consists of 66 satellites that provide seamless global coverage. Last but not least, NTN can be an invaluable resource during emergencies.

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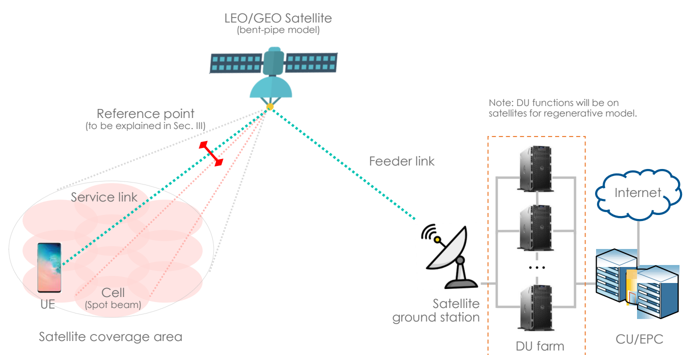


Figure 1: Overview of satellite communications

3GPP has adopted a phased approach for the standardization of NTN. A new study item (SI) for NR to support NTN was conducted during Release 15; the results of this SI were summarized in [1]. A second-phase SI was conducted during Release 16; the results of this SI were summarized in [2]. A work item (WI) for solutions for NR to support NTN is being conducted in Release 17. A related SI for Narrowband-Internet of Things (NB-IoT) and enhanced Machine Type Communication (eMTC) support for NTN is also being conducted in Release 17.

Table I: Comparison of different types of satellites

Satellites	GEO	MEO*	LEO
Orbit	Fixed with respect to a given location on Earth	Circular around the Earth	
Typical altitude (km)	35786	8000 – 20000	500 - 2000 (Note: Very LEO (VLEO) satellites can operate below 500 km.)
Typical beam footprint size (km in diameter)	200 – 3500	100 – 1000	100 - 1000
Advantages	• Larger coverage • Negligible Doppler shift (due to notional stationarity)	Lying between LEO and GEO	• High throughput • Low latency • Low cost and weight (Note: VLEO exploits further cost/weight reduction.)
Disadvantages	• Low throughput • High latency • High cost and weight		• Smaller coverage • Large Doppler shift (due to high orbital velocity)

*Note: MEO satellites are a good tradeoff between LEO and GEO satellites, as they have 1) larger beam footprints than LEO and 2) lower delays than GEO. Many navigation systems, including GPS, Galileo, and GLONASS, exploit this tradeoff.

In early 2020, the HAPS Alliance was formed to promote the use of HAPS. Drones and balloons are collectively termed HAPS, which have an altitude of 20-50 kilometers; in contrast, LEO satellites have an altitude of 200-2000 kilometers. Therefore, a HAPS node can support relatively low communication latencies; however, air currents complicate the task of maintaining its position, and its flight time is significantly shorter than that of a satellite. Also, in late 2019, the Alliance for Telecommunications Industry Solutions (ATIS) formed an NTN 5G Integration Working Group.

Fixed-satellite services (FSS), which generally require dish-style antennas such as Very Small Aperture Terminal (VSAT) for reception, have dominated satellite communications for decades. Yet the growing need for limitless connectivity is fueling the growth of mobile-satellite services (MSS). MSS provides global voice and data communications to on-the-go and remote users via smaller, more lightweight User Equipment (UE). Current MSS systems, such as Iridium, require a dedicated UE for satellite communications that differs from a smartphone. Thus, legacy satellite communications systems have mandated that users carry a separate device for satellite access. On the other hand, increasing user dependence on smartphones has motivated recent studies of smartphone-enabled MSS, where the main use cases include pedestrian, IoT connectivity, and public safety with performance targets of 2 - 3.5 Mbps for DL and 10 kbps - 3.5 Mbps for UL.

NTN differs from TN in that it supports 1) much larger distances between the BS and the UE, and 2) mobility of non-GEO (NGSO) satellites and HAPS (in contrast, the BS is always stationary in a TN). These differences are inherent to satellite communication and affect NR NTN system design as summarized below.

Excessive propagation delay: The round-trip time (RTT) in a TN is less than 1 millisecond (ms), even in an extremely large cell with a radius of 100 km; in contrast, the RTT in an NTN ranges from tens to hundreds of ms depending on satellite altitudes and payload types [1]. For a GEO satellite that supports a transparent payload, the RTT between a UE and the BS on the ground can be 477.5 ms. Such long latencies cannot be handled by the current NR protocols, which were originally designed without considering NTN. For example, a UE cannot employ the legacy initial access procedure due to limits on the timing advance and scheduling timing offset during random access. Also, for a Hybrid Automatic Repeat Request (HARQ) retransmission scheme, a new transmission or a retransmission for a given process can be initiated based on HARQ acknowledgement (ACK) feedback - which will experience a long RTT in NTN. While all HARQ processes wait for this feedback, there can be a *stop and wait* duration without any transmissions. This scenario is termed *HARQ stalling*, which reduces peak data rates - limiting the range of services offered by NTN.

Limited link budget: As shown in Table II, satellite communications suffers from high propagation losses; thus, the link budget is extremely limited, especially for UL communications. That is, UL communications between a mobile phone and a satellite typically occurs over bandwidth-constrained low-frequency bands, due to transmit-side power constraints and the inherent difficulty of integrating a high-gain antenna into a mobile phone with a small form factor. To improve the link quality, Peak-to-Average-Power-Ratio (PAPR) reduction techniques such as low-PAPR modulations or waveforms can be considered, along with coverage enhancement solutions such as repetitions. Low PAPR modulations/waveforms support power amplifier operation over a higher input power range, improving the link budget or, equivalently, extending coverage.

Large Doppler shift: For LEO satellites, communication links experience large Doppler shifts due to high orbital velocities. The Doppler shift depends on 1) the relative speed between the transmitter and the receiver and 2) the carrier frequency; it increases at lower satellite altitudes and higher carrier frequencies. For example, the maximum Doppler shift for a LEO satellite operating at 2 GHz at an altitude of 600 km is $\pm$46 kHz, which is comparable to the NR subcarrier spacing options of 15/30/60 kHz for sub-6 GHz bands [1] (in contrast, the maximum frequency offset in a TN is typically less than 10 kHz). Large Doppler shifts would impact synchronization

Table II: Link budget analysis at carrier frequency of 2 GHz

Satellites	GEO		LEO (1200 km)		LEO (600 km)	
Link parameters	**DL**	**UL**	**DL**	**UL**	**DL**	**UL**
Tx transmit power (dBm)	52.77	23.00	54.77	23.00	48.77	23.00
Tx antenna gain (dBi)	51.00	0.00	30.00	0.00	30.00	0.00
Rx antenna gain (dBi)	0.00	51.00	0.00	30.00	0.00	30.00
Noise figure (dB)	7.00	7.00	7.00	5.00	7.00	5.00
Distance (km)	40317.35		1999.45		1075.46	
Free space pathloss (dB)	190.58		164.49		159.10	
Receive SNR (dB)	0.00	-7.12	7.19	-2.66	6.57	2.73

Note: DL channel bandwidth is assumed to be 30 MHz for GEO/LEO. UL channel bandwidth is assumed to be 180 kHz for GEO and 360 kHz for LEO. The reception elevation angle is assumed to be 12.5° for GEO and 30° for LEO. Additional losses include atmospheric loss of 0.2 dB, shadow fading margin of 3 dB, and scintillation loss of 2.2 dB.

and measurements, among other procedures.

Frequent handover: Due to the high orbital velocities of LEO satellites, the time window for a UE to remain within a cell (or a spot beam) is very short, e.g. a few minutes. Fast-moving beams pose the challenge of frequent handover, which is exacerbated when handover must be performed for a large number of UEs. In that case, connection interruptions will occur frequently if handover is not performed efficiently.

In this article, we focus on direct communication between satellites and cellular phones; we discuss standardization activities, key technical issues, and potential solutions – including the demonstration of a proof-of-concept (PoC) system – to realize satellite-enabled global communications.

II. Overview of Satellite Communications

A. *Comparison of Different Types of Satellites*

The most common types of satellites are GEO and NGSO. There are two main types of NGSO satellites: LEO and MEO. Detailed comparisons between GEO, MEO and LEO satellites are shown in Table I. For example, a GEO satellite appears to be stationary with respect to a fixed position on Earth; this relatively large satellite, which operates at a relatively high altitude, uses hundreds of spot beams to support a wide coverage area. As illustrated in Figure 1, a spot beam can be viewed as a TN cell; also, the typical beam footprint, as shown in Table I, is much larger than a typical terrestrial macro cell (which has a diameter of 1-20 km). On the other hand, the size and cost of an NGSO satellite have decreased over time, as the process of manufacturing and launching it is optimized (e.g. the development of reusable launch vehicles); that will fuel new opportunities for satellite communications. In contrast, a LEO satellite orbits the Earth at a relatively low altitude - supporting lower latencies, improved link budgets and higher throughputs. However, a LEO satellite 1) only uses tens of spot beams to support a relatively narrow coverage area and 2) has a relatively large orbital velocity, resulting in more frequent handovers and large Doppler shifts. Since LEO satellites operate at lower power levels, compared to MEO and GEO satellites, they are relatively small; thus, they employ fewer spot beams. Also, high Doppler shifts complicate the task of frequency tracking at the UE. MEO satellites (e.g. the Galileo system) orbit the Earth at a wide range of altitudes between those of LEO and GEO satellites.

Satellites, regardless of their orbits or altitudes, can support either transparent payloads (often referred to as a bent pipe) or regenerative payloads [2]. A satellite that supports a transparent payload can perform radio frequency (RF) filtering, frequency conversion, and amplification. In terms of the 3GPP-defined disintegrated 5G BS, a satellite that supports a transparent payload has an on-board radio unit (RU); the distributed unit (DU) and centralized unit (CU) are on the ground behind the ground station, as illustrated in Figure 1. In contrast, a satellite that supports a regenerative payload can *also* perform encoding/decoding, modulation/demodulation, and scheduling/switching/routing. Thus, a satellite that supports a regenerative payload *also* has at least some on-board CU/DU functionality. Also, inter-satellite links are optionally considered for satellites that support regenerative payloads - but not for those that support transparent payloads, as those satellites do not need to be directly connected.

To provide insights on the link quality for different types of satellites, we conduct the link budget analysis in Table II. This analysis shows that the link budget of LEO satellites is better than that of GEO satellites due to their lower altitudes. Also, the quality of the uplink (UL) channel is lower than that of the downlink (DL) channel, due to the limited transmit power of the mobile UE.

B. *Spectrum Usage*

Most satellites use L/S/C or Ku/Ka bands for communications, as shown in Figure 2. The choice of a frequency band is generally determined by 1) the target service type, i.e., MSS or FSS, or 2) the link type, i.e., access or feeder - instead of the satellite type as discussed in Section II-A. Low-frequency bands such as L/S are commonly used for an MSS access link; for a mobile device, it is difficult to integrate a high-gain antenna and align the beam direction with a satellite, due to user mobility and the device form factor. Thus, employing a low-frequency band, which has lower path loss and signal directivity, is beneficial in providing reliable connectivity. For instance, Iridium, which provides MSS using LEO satellites, uses the L band for its access link. In contrast, high-frequency bands such as Ku/Ka are commonly used for an FSS access link; in this case, UEs are generally equipped with high-directivity VSAT antennas. Also, beam alignment can be easily achieved, as the relative movement between the UE and the satellite is either 1) negligible or 2) predictable based on

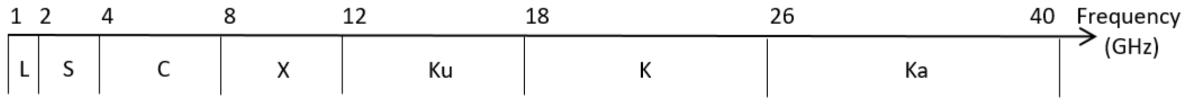


Figure 2: Institute of Electrical and Electronics Engineers (IEEE) radar bands

orbital dynamics. For instance, Starlink, which provides FSS using LEO satellites, uses the Ku band for its access link and the Ka band for its feeder link. On the other hand, the Federal Communications Commission (FCC) recently opened up the tera-hertz (THz) band. While it has not been considered for satellite communication, it can support FSS due to its extremely wide bandwidth (in conjunction with high-gain beamforming).

Another important consideration for satellite spectrum allocation is the resulting interference between an NTN and other NTNs and TNs. The ITU Radiocommunication Sector (ITU-R) has constrained the interference of LEO and MEO systems to any GEO network. Also, the FCC has constrained the co-channel interference between an NTN and other NTNs and TNs - thereby constraining the radiated power of a UE. 3GPP is studying the co-channel interference between NTNs and TNs.

III. 3GPP NTN Standardization

3GPP is the primary standardization organization defining NTN based on NR radio access technology. Development of a satellite-mobile direct communication system within a global standard provides several benefits that cannot be obtained with proprietary solutions (e.g. Iridium), including interoperability between different vendors, seamless interworking with 3GPP-based cellular TN, seamless integration with cellular smartphones, and the ability to leverage the advanced radio access technology of NR.

Timing relationship enhancement: The large propagation delays in NTN imply that many timing relationships, especially those involving DL-UL interactions, i.e. consecutive messages exchanged between a BS and a UE, require enhancements, as illustrated in Figure 3. For instance:

- The duration between the transmission of a UL scheduling grant and the transmission of the corresponding Physical Uplink Shared Channel (PUSCH) in NTN exceeds the current maximum scheduling timing delay in NR.
- The HARQ-ACK feedback from a UE to the BS for Physical Downlink Shared Channel (PDSCH) reception experiences a delay that exceeds the supported maximum feedback delay in NR.
- The timing regarding the action and/or UE assumption on the DL configuration indicated by the MAC Control Element (CE) will be impacted.
- The timing relationship between DL channel state information (CSI) report triggering and the reception of a CSI report at the BS will be impacted.
- The timing relationship between aperiodic Sounding Reference Signal (SRS) triggering and the reception of a UL SRS at the BS will be impacted.

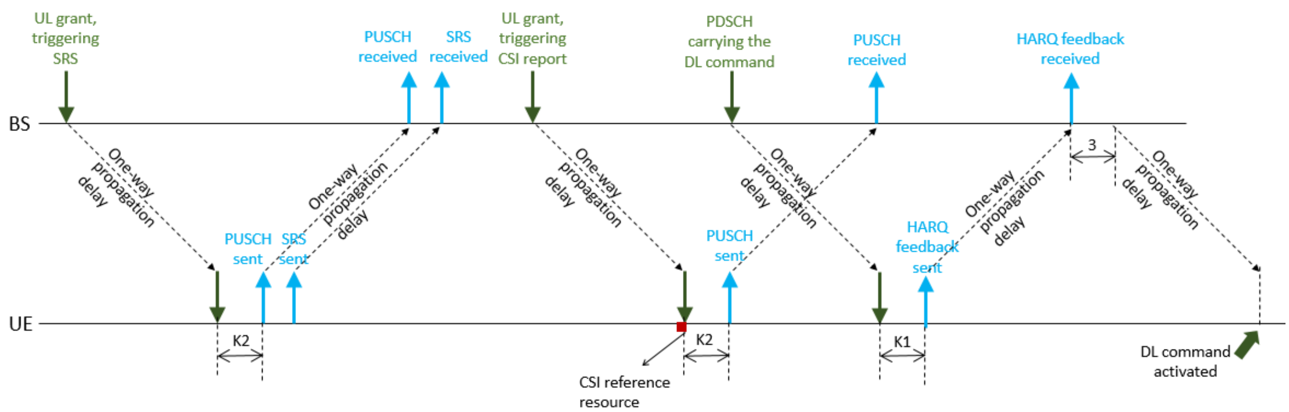
To address these issues, a timing offset is introduced for the above-mentioned timing relationships. The offset used in initial access is configured in the broadcast system information. The timing offset can be updated after the UE enters Radio Resource Control (RRC) connected mode.

Uplink timing and frequency synchronization: The issues of excessive propagation delays and large Doppler shifts motivate enhancements on UL timing and frequency synchronization. For uplink timing synchronization, solutions to these issues rely on the concept of a common timing advance (TA) value, which is determined with respect to a single reference point in a given satellite beam/cell, as shown in Figure 1. The common TA value can optionally include the propagation delay over the feeder link. In Release 17, a UE is assumed to have a Global Navigation Satellite System (GNSS) implementation, which leverages the knowledge of its position and received satellite ephemeris information to compute a UE-specific differential TA value. A UE in RRC idle/inactive mode applies a common TA value that the network indicates (in addition to its computed UE-specific differential TA value) before it sends a Physical Random Access Channel (PRACH) preamble. A UE in RRC connected mode also uses TA adjustment commands from the BS to update the TA value that it applies. For uplink frequency synchronization, to overcome large Doppler shifts, a UE that has a GNSS implementation leverages the knowledge of its position and received satellite ephemeris information to determine and pre-compensate a UE-specific frequency offset.

HARQ enhancements: Two main solutions for the previously-described HARQ stalling issue are being discussed:

- Disabling of HARQ-ACK feedback for DL reception is now supported, allowing the BS to continuously transmit data without waiting for HARQ-ACK feedback; failed transmissions are handled by the Radio Link Control (RLC) layer ARQ protocol. The disadvantage of RLC-layer ARQ is the dullness of error correction. Enabling/disabling HARQ-ACK feedback can be configured per HARQ process via UE-specific signaling.
- The maximum HARQ process number has increased from 16 to 32. This enhancement will be especially meaningful for LEO satellites with relatively small latencies, compared to GEO satellites; it also enables the BS to continuously provide DL/UL scheduling for a given user, increasing the expected throughput.

Polarization mode configuration/signaling: The polarization of an electromagnetic wave is determined by the direction of oscillation of its electric field. Examples include 1) linear polarization, where the electric field oscillates in a straight line (generally assumed for mobile UEs) and 2) circular polarization, where the electric field rotates about the direction of wave



Note: K1 (with range of 0 to 15 slots) and K2 (with range of 0 to 32 slots) are parameters defined in NR for HARQ feedback timing from the PDSCH reception and PUSCH transmission timing from the UL grant reception, respectively.

Figure 3: The impact of long propagation delay on various DL-UL timing relationships

propagation (generally assumed for satellites and VSAT-type UEs). Circular polarization can be further differentiated as left-hand circular polarization (LHCP) or right-hand circular polarization (RHCP), depending on whether the direction of rotation is clockwise or counter-clockwise. Circular polarization has been widely used in satellite communications to double the spectral efficiency, as the same time-frequency resources can be reused between LHCP and RHCP. As the polarization directions between the transmitter and the receiver need to match to optimize the system performance, the network will explicitly indicate the polarization direction that it uses for downlink transmissions to the UE. A mobile UE with a linear-polarized antenna can receive signals from satellites that use circular polarization, albeit with a 3 dB depolarization loss.

Random access: In the random access procedure that UEs utilize to acquire UL synchronization or request UL resources, a UE first sends a PRACH preamble and then waits for a certain duration (i.e. the RAR window) for the random access response (RAR) from the BS. The delay from the PRACH transmission to the start of the RAR window in current NR systems is at most 160 ms (in addition to the maximal RAR window size of 10 ms), which cannot accommodate the large RTT for GEO satellites. Thus, an offset has been introduced to the start of the RAR window to address this issue.

Mobility enhancements: Solutions must be developed to address the issue of frequent handover due to movement of NGSO satellites. Also, large RTT introduces long latencies to mobility signaling, impacting the service interruption time. In addition, it has been determined that the difference in signal strength (or, more generally, the radio resource management (RRM) metric) between overlapping beams may be negligible, due to large distances between UEs and satellites. This motivates enhancements to 1) reduce service interruption during handover and 2) improve handover robustness. Thus, NR introduced the conditional handover (CHO) scheme as an outcome of the Release 16 mobility enhancement WI, where a handover is executed by the UE when one or more handover execution conditions are met. CHO has been identified as an efficient and robust procedure for handover in NTN. In addition to the RRM metric-based conditions for CHO, time/timer-based and location-based triggering conditions would be added for NTN to address negligible differences in the RRM metrics between overlapping beams. Also, discussions concerning other handover enhancements are on-going in 3GPP, including methods to reduce mobility interruption time such as Random Access Channel (RACH)-less handover, support of location-based measurement, etc.

For idle mode cell selection/reselection, the schemes in NR will serve as baseline methods, while a satellite/HAPS ephemeris-based scheme would be defined for NTN to improve the cell selection/reselection performance; discussions concerning this scheme are on-going in 3GPP.

IV. Demonstration of a PoC System

To validate the previously-discussed NTN solutions, we developed a satellite communications PoC testbed as shown in Figure 4. While LTE is used for this PoC (due to the availability of relatively mature open-source software-defined solutions for LTE), the modifications that we implemented are necessary and applicable to both LTE and NR. While there have been similar demonstrations over actual satellites [3], the main purpose of this PoC entailed validating the feasibility of the latest protocol-level NTN solutions developed by 3GPP (*not* the demonstration of satellite communications) prior to commercial development of NTN systems based on Release 17.

The PoC testbed consists of two separate desktops that were set up with srsLTE [4], an open-source software-defined solution for LTE. One desktop was configured to run a 4G Evolved NodeB (eNB) and Evolved Packet Core (EPC), while the other was configured to run the UE. Each desktop was connected to a Universal Software Radio Peripheral (USRP) N310. The USRPs were cabled to a Satellite Channel Emulator [5] programmed to add 300 ms of delay to both the uplink and downlink channels with no Doppler shift, mimicking a GEO satellite that supports a transparent payload. The system was configured to operate on LTE Band 3, with DL frequency

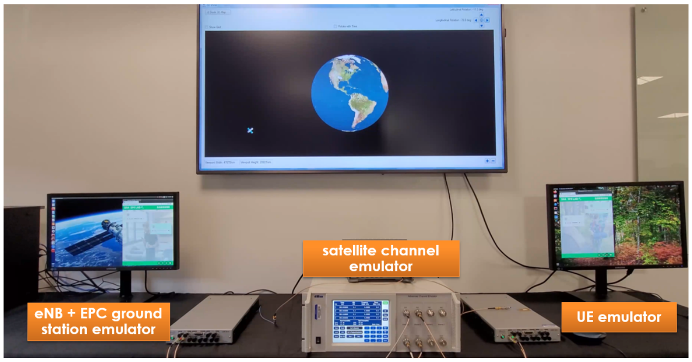


Figure 4: Software-defined satellite testbed

at 1805 MHz and UL frequency at 1710 MHz. The system bandwidth was set to 10 MHz.

The srsLTE source code was modified to support an RTT of 600 ms, which significantly exceeds the latency in a conventional TN. First, the timing relationships in the random access procedure were altered so that the UE could successfully attach to the network before the procedure was abandoned. After completing the random access procedure, a radio bearer was attached to the UE, and data was scheduled. To accommodate long latencies, the timing relationship between the transmission of a UL scheduling grant and the transmission of the corresponding PUSCH was adjusted, ensuring that the eNB could expect - and receive - the corresponding UL data at the proper time. Also, HARQ operation was disabled to address the previously-described HARQ stalling issue; error correction relied on the RLC-layer ARQ protocol.

The UE desktop includes srsLTE UE and App blocks. To demonstrate network connectivity, we performed ping and iperf over this setup; we observed minimal packet loss and an average ping delay of just over 600 ms, showing a baseline level of bidirectional communication over the emulated satellite channel. We then extended the functionality to highlight promising use cases for satellite communications. While the throughput was somewhat limited, we successfully demonstrated a variety of functions including text messaging, file upload, and push-to-talk (PTT) functionality. Furthermore, with the core network performing network address translation (NAT), the UE was able to browse the Internet.

V. Research Areas for Further Enhancement

While satellite communications is attracting growing interest, the previously-described solutions should be viewed as intermediate steps in the journey to exploit the full potential of NTN. As shown below, several open issues must be addressed to reach that goal.

One critical open issue concerns further enhancements of communication mechanisms and procedures to mitigate the effects of satellite motion and long latencies. For example, the synchronization and reference signals can be enhanced to improve the synchronization and measurement performance with large Doppler shifts. Also, the differences in UE-BS propagation distances in NTN can significantly exceed the maximum propagation distance difference of 200 km that is supported by the current NR PRACH. This issue, along with possibly large Doppler shifts, necessitates the development of enhancements for PRACH signaling. For example, Release 17 NTN relies on the assumption that a UE can use GNSS signals to determine its position - implying that a low-cost UE without GNSS capability or UEs that receive weak GNSS signals cannot access an NTN system. Thus, new PRACH formats and mechanisms are required to support such UEs.

Also, adaptive modulation and coding schemes and power control schemes that can mitigate the effects of long latencies need to be developed. Another critical open issue concerns the interworking of NTN and conventional TN. Despite some related work [6] [7], issues related to spectrum sharing, communication across different platforms, interference management and offloading need to be addressed.

Emerging machine learning techniques are inspiring novel enhancements for NTN. Some of the open issues that may be addressed by these techniques include channel status prediction/estimation, handover optimization, adaptive beamforming, adaptive resource allocation in NTN-TN overlay networks, and management of satellite constellations.

Other open issues include collision avoidance for congested orbits, management of space junk due to the short lifetime of LEO satellites, and management of potential interference hazards due to an increasing number of satellites.

VI. Conclusions

This overview of NTN-enhanced cellular networks has highlighted several motivating use cases. NTN-enhanced cellular networking differs from conventional satellite communications in that it has fostered industry-wide development of standards-based solutions – facilitating truly global communications. While significant challenges remain in realizing this vision, recent NTN-enhanced cellular network deployments and rapid progress in the development of standards-based solutions indicate that they are not insurmountable. Addressing these challenges will allow users to realize the promise of global 5G (and beyond) communications.

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