Review on 5G Non-Terrestrial Networks Using OpenAir Interface: An Experimental Investigation Using GEO Satellites

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ABSTRACT The Third Generation Partnership Project (3GPP) aims to integrate terrestrial 5G networks with non-terrestrial networks (NTNs). Prototyping and testing play an essential role in demonstrating that new 5G-NTN releases are ready. However, universities and nonprofit research organizations struggle to modify and customize commercial 5G protocol stack implementations for 5G-NTN testing and development, as these solutions are often costly and proprietary. A promising alternative is software-defined radio testbeds that use open-source software. This article describes our protocol stack modification of an open-source 5G-NTN implementation based on OpenAir Interface (OAI), which runs on standard hardware. We use a transparent geostationary satellite to evaluate our 5G-NTN's performance across different layers in real-world conditions. To validate our testbed, we use various online applications, including voice over IP, web browsing, and video streaming. The results indicate that the current implementation, which operates with a 5MHz bandwidth, is reliable over several hours and maintains a typical geostationary latency of around 530ms while achieving download and upload speeds of 3.6Mb/s. The tests confirm that our 5G-NTN testbed is a reliable alternative to costly commercial solutions.

INDEX TERMS: space communications, satellite communication, 5G mobile communication, and radio access networks.

I. INTRODUCTION

Fifth-generation mobile networks' (5G) terrestrial infrastructure is not enough to deliver seamless connectivity to underserved and unserved regions of the planet. 5G base station deployment is not logistically or financially viable in some places. Communication has advanced to a previously unheard-of level and is now able to deliver services that demand high bandwidth and throughput. Satellites are perfect partners for 5G networks because of their wide availability and broad coverage. Satellites can improve 5G networks' coverage, resilience, and dependability, which will raise the networks' worth.

The potential function of communication satellites in enhancing a terrestrial network (TN) was recognised in 3rd Generation Partnership Project (3GPP) Releases 15 [1] and 16 [2]. Deployment scenarios, channel models, frequency ranges, satellite constellations, access modes, footprints, and antenna models were all thoroughly examined as a result. In March 2022, the first specifications for integrating satellites into 5G were finalized [3]. With an emphasis on offering direct access to 5G services at the user terminal, satellites were for the first time taken into consideration outside of a transport network. This indicates that a ground-based next-generation node B (gNB) is directly connected to the user terminal through a satellite channel (Figure 1). However, it is more difficult to integrate 5G TN and NTN components. Satellite channels were not taken into account in any of the early deployment scenarios for the development of the 5G new radio (NR) TN protocol stack. Therefore, before 5G-NTN-based services can be implemented, considerable adjustments are required.

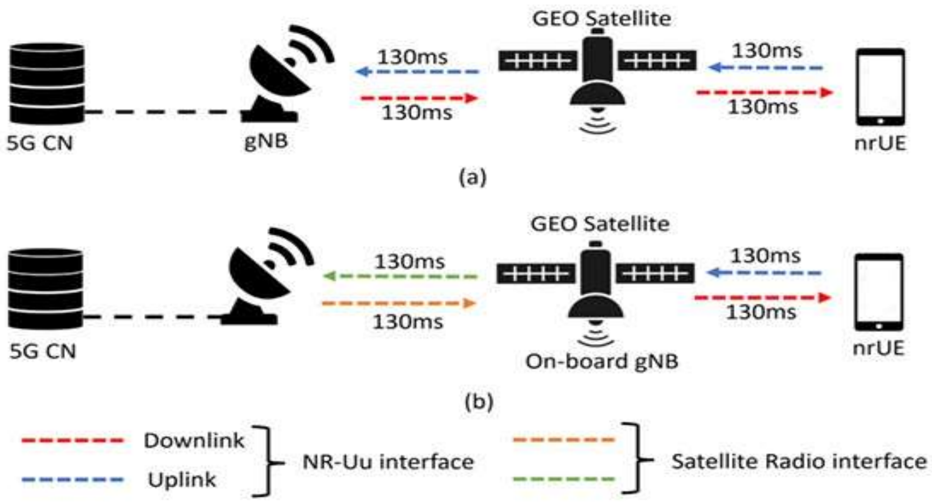


FIGURE 1. High-level 5G-NTN architecture using (a) a transparent-payload geostationary satellite and (b) a regenerative-payload geostationary satellite with on-board gNB. Note that the one-way delay for (a) is ~ 260 ms, whereas that for (b) is ~ 130 ms.

To overcome the difficulties presented by the GEO satellite channel, modifications were made to the terrestrial protocol stack of OpenAir Interface (OAI) [7], an open-source software defined radio (SDR) framework that implements 4G/5G base stations and user terminals. For live experiments over the satellite [9] and in-lab validation [8], we created a PoC demonstrator. We aim to assess the performance of common internet applications, including transport protocols, voice over IP (VoIP) calls, video streaming, and web browsing. We carry out experiments in this study and report the results. Researchers can now access the modified source code under the terms of the OAI Public License V1.1 [10]. The rest of this paper is structured as follows: The difficulties with 5G NR-based NTN are discussed in Section II. The modifications for GEO satellites in OAI are explained in Section III. The measurement setup is shown in Sections IV and V, along with the evaluation and measurement outcomes. We suggest directions for future research in Section VI. In Section VII, we finally present the findings.

With assistance from government space agencies and industry, academic researchers have created a number of Proof of Concept (PoC) demonstrators for 5G-NTN in recent years. Open research platforms, like 5G NTN testbeds, are crucial for streamlining the creation of standardised prototypes [5], as 3GPP standardisation further optimises the 5G-NTN in Releases 18 and 19 [4]. By offering a safe and regulated setting for testing and assessing cutting-edge technologies, these testbeds are essential to research and standardisation. The creation of upcoming NTN specifications depends on these. Prior to deployment, the testbeds make sure the new NTN standards are safe, dependable, and affordable.

II. CHALLENGES IN THE 5G-NTN

There are a number of difficulties in deploying 5G-NTN with GEO satellites. The satellite amplifies the incoming ground signal and converts the frequencies before reflecting it back to the ground in a transparent payload configuration. Because existing satellites can be used, this configuration facilitates the deployment of 5G-NTN; however, as Figure 1 [11] illustrates, the round-trip delay (RTD) between the g NB and user equipment (UE) is doubled when compared to regenerativepayload satellites. In our research, we looked at a transparent-payload GEO satellite; the difficulty arises from the satellite's considerable separation from Earth.

The following problems result from this: Table 1 shows that the RTD between the g NB and UE is approximately 520 ms. Due to the closed-loop nature of the protocols, this violates them at every layer. A closed-loop system's timers are designed to endure the greatest amount of delay that can occur on Earth's surface. As a result, modifications are required at every protocol layer. b The high path loss brought on by the great distance between the UE and the satellite—particularly with GEO satellites orbiting at 35.786 kilometers—is another issue facing 5G-NTN. We go over a few of the main issues raised by the transparent-payload GEO satellite-based 5G-NTN below.

A. RANDOM ACCESS

The random access (RA) process is started by an active UE following initial downlink synchronisation [13]. The UE decodes the information transmitted on the broadcast channel by the gNB, sends message-1 (MSG-1) on the physical Random-Access channel (PRACH), and then waits for MSG-2 from the gNB. The time the UE waits is called the random-access response

TABLE 1. Typical round-trip delays in terrestrial and non-terrestrial systems [12].

Technology	Height/orbital altitude	Possible cell/beam size	Max. round-trip delays
cellular macro	10 m to 25 m	500 m	0.016 ms
cellular rural	35 m	5 km	0.16 ms
LEO	600 km	50 km to 90 km	~ 26 ms
GEO	35 786 km	120 km	~ 520 ms

(RAR) window. It waits for MSG-4 after sending MSG-3 to the gNB after receiving MSG-2. The contention resolution timer (CRT) is the name given to this waiting period. The UE resends the relevant message if it does not receive MSG-2 or MSG-4 within a specified time frame. The exchange of these messages is depicted in Figure 2. The gNB at the UE does not respond when the 5G-NTN is deployed over GEO satellites using the same RAR and CRT timeout window as for the TN. As a result, the RTD needs to be increased in proportion to the window for reception [2].

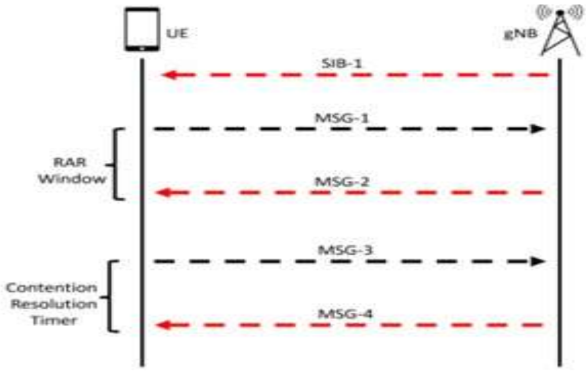


FIGURE 2. Messages exchanged between the UE and gNB during the random access process, along with the associated random access response window and contention resolution timer.

B. HARQ REACTIONS

Hybrid automated repeat request (HARQ) is a 5G wireless communication error correcting technique. As a stop-and-wait protocol, HARQ gives each running HARQ process a unique ID. The ID can only be used once the pertinent feedback has been received. The TN version of 5G has 16HARQIDs, which allows for 16 parallel transmissions. After transmission, each HARQ ID awaits an acknowledgement (ACK) or no acknowledgement (NACK). Nevertheless, a transparent payload GEO satellite has an unusually long feedback waiting period, which means that a particular HARQ ID won't be accessible during that time. There might be a scenario where a shortage of available HARQ process IDs prevents further data transmission if the current protocol stack is maintained.

This situation, sometimes referred to as "HARQ stalling," is particularly challenging in a GEO context because of the incredibly high RTD, which requires an irrational number of process IDs for HARQ, according to [14]. In [2], it was decided to disable the HARQ feedback so that transmission could continue without the HARQ process waiting for the ACK/NACK signal. In these cases, retransmission is either handled by an automatic repeat request (ARQ) in the radio link control (RLC), as demonstrated in [15], or it is fully delegated to the transport layer protocol, as in the transmission control protocol (TCP).

C. BUFFERS, OFFSETS, AND TIMERS

All of the timers and buffers in the protocol stack are affected because the 5G-NTN has a higher RTD than the TN. Early expiration will affect the medium access control (MAC), radio resource control (RRC), packet data convergence protocol (PDCP), and RLC layers. Additionally, the gNB needs to adjust the time-slot difference between the matching gearbox and reception. This subject is discussed below.

1) k offset (MAC)

The UE broadcasts in slot n + k2 after receiving downlink control information (DCI) in DL slot n. The uplink (UL) slot is PUSCH, which is based on an offset of k2.

The current range of k2 values (0–32) is insufficient to handle the enormous RTD of the NTN, especially when the timing advance (TA) applied by the UE is also much greater than k2 [16].

Consequently, another offset is required to produce the complete offset, n + k2 + k offset. An illustration of this process is shown in Figure 3. This k offset is a part of the timing relationship upgrades and is utilised for several physical layer operations, such as extending the RAR and the contention resolution window.

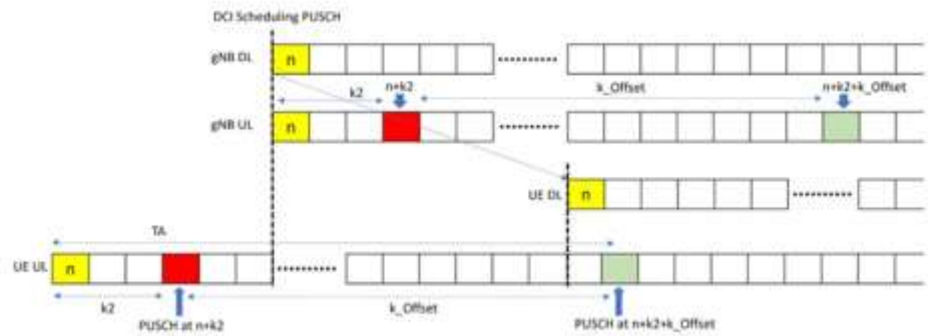


FIGURE 3. **Illustration of uplink scheduling with and without k_{offset} [16]. The k_{offset} must be adjusted according to the round-trip delay.**

2) PDCP (t-Discard Timer)

This timer applies to the transmitter-side PDCP entities. The PDCP entities store the service data unit (SDU). Start the t-Discard Timer after moving it from the top layer of a transmission buffer to the RLC. The timer can be turned off by setting it to an infinite duration or between 10 and 1500 milliseconds, per [17]. When the t-Discard Timer on a PDCP SDU runs out or the successful The transmitting PDCP entity discards the buffered PDCP SDU and the corresponding PDCP protocol data unit (PDU) after the peer PDCP entity verifies the delivery of the PDCP SDU (via the PDCP status report).

3) The PDCP (t-Reordering Timer)

This timeframe applies to the receiver-side PDCP entities. The t-Reordering Timer is used to detect the loss of any RLCPDU in the lower layers, which is the acknowledged mode of an RLC entity's receiver side (AM).

4) The t-Reassembly Timer (RLC)

This timer applies to the RLC that receives entities. The RLC that receives the entity reassembles PDUs in unacknowledgment. Edged mode (UM) and AM. Finding potential RLC PDU loss in the lower tiers requires this process. The timer t-Reassembly begins and waits for the missing PDU if the PDUs inside the receive window are not sequential.

When the tReassembly timeout expires, the receiving entity sends any PDUs with consecutive packets before or after the sequence gap to the top layers. The t-Reassembly configuration allows fixed values between 0 and 200 ms, per [18].

III. OPENAIR INTERFACE ADAPTATIONS

In order to address the problems mentioned in Section II, we modified the protocol stack in the 5G-GOA project. Using the OAI 5G-TN version as the baseline, we achieved significant gains. alterations [5]. Importantly, no changes were made to the air interface. We used the 5G-TN
waveform for the air interface in 5G-GOA. We also introduced a new graphical user interface (GUI) for OAI based on the QT-GUI. The following features were specifically added to the OAI physical layer (PHY) and MAC: The features include: i) the integration of multiple bandwidth parts (BWPs); ii) support for a 5 MHz bandwidth with a 15 kHz sub-carrier spacing (SCS); iii) comprehensive MAC-level frequency division duplex (FDD) scheduling, which allows for continuous downlink (DL) and UL transmission and reception; iv) improved support for multiple UEs with enhancements for simultaneous RA; and v) an enhanced "disable HARQ" feature to enhance collaboration with the upper layers, particularly the PDCP and RLC.

A. MACLAYER AND PHY MODIFICATIONS

We added a standard delay parameter to the command line for the TA. Consequently, the RTD is supplied to the UE as a command line argument for the first TA. This command line option is essential because our gNB does not broadcast serving-satellite ephemeris. Our TA command transmission takes into account a delay that is at least twice as long as the one-way delay between the gNB and UE. This TA command in the MAC control element is transmitted from the gNB to the UE in order to maintain UL synchronisation in the time domain. The TA periodicity was changed so that our UE could provide closed loop TA updates in any circumstance.
Additionally, we built a method where our UE considers an offset at the start of the RAR window using the same command line argument that is applied to the TA. This suggests that the start of the RAR window is delayed using an estimate of UE-gNB RTD. A key part of our connection establishment method, the RA procedure, required some changes to support the simultaneous RA process for many UE. In order to select a preamble index during MSG-1 creation, the UE generates a random number. it was necessary to develop a random number based on the CPU count cycle in order to improve this preamble selection method.

Layer	Modifications
PHY	Extension of OpenAirInterface RF-simulator to support simulation of long propagation delays Non-NTN-specific features: - Support of 5 MHz bandwidth (15 kHz subcarrier spacing) - Phase tracking reference symbols - Support for bandwidth parts
MAC	Hybrid automatic repeat request (ARQ) feedback deactivation at gNB and UE Adaptations to support uplink timing advance and random access procedures Frequency division duplex scheduling
RLC	Disabling hybrid ARQ - ARQ interaction Increase ARQ buffer size Increase maximum sequence numbers
PDCP	Increase Discardtimer to the currently maximum allowed value Increase t-Reordering timer to the currently maximum allowed value Increase protocol data unit buffer size Increase maximum sequence numbers
RRC	Timers T300, T301 and T311 are set to the currently maximum allowed value
Misc	New QT based KPI-GUI

As decided for the 5G NR-NTN in Release 17, we implemented a k2 offset value called k offset on both the gNB and UE sides in our OAI 5G NR-NTN implementation. this offset to the k2 value shown by the DCI. The k offset value is sent as a command line parameter to gNB and UE. Moreover, an update of the k offset value is superfluous in our situation with GEO satellites, where the TA update mechanism suffices. Consequently, our system forbids changing the k offset value after initial access. Additionally, since DL and UL frame times are synchronised at gNB, k mac was not necessary in OAI.

B. ADAPTATIONS TO HIGHER LAYERS

Due to the high RTD brought on by the 5G-NTN link, we also increased the discard value. A timer that can cover several cumulative maximum durations; if this isn't adjusted, the timer expires too soon, leading to the premature disposal of the SDU. Furthermore, increasing the t-Discard Timer setting expands the transmitter's buffer capacity because it has to store both incoming SDUs and SDUs that are still awaiting received receipts. Similarly, for the t Discard Timer setting, we increased the t-Reordering timer to take into consideration the cumulative maximum delays. According to [17], the RRC determines the t-Reordering timer value, and the maximum period is 300ms.

To compensate for the latency caused by large RTDs, we increased the value of the t-Reassembly timer. When HARQ is enabled, t-Reassembly should also account for the maximum time allowed for HARQ retransmissions, which may be longer than the RTD. This ensures accurate data reconstruction by accounting for the HARQ delay during the reassembly process. Since the modifications in RLC, PDCP, and RRC were sufficient, there was no need to alter the non-access stratum (NAS). The DLHARQ processes in OAI gNB and OAIUE can be fully enabled or disabled
using command line parameters. Releases 15 and 16 state that if HARQ is enabled, there can be no more than 16 HARQ processes.
However, using HARQ for GEO satellite-based 5G-NTN is not advised due to the substantial additional latency that causes "HARQ stalling." Therefore, we completely disabled HARQ using command line parameters.

IV. MEASUREMENT SETUP

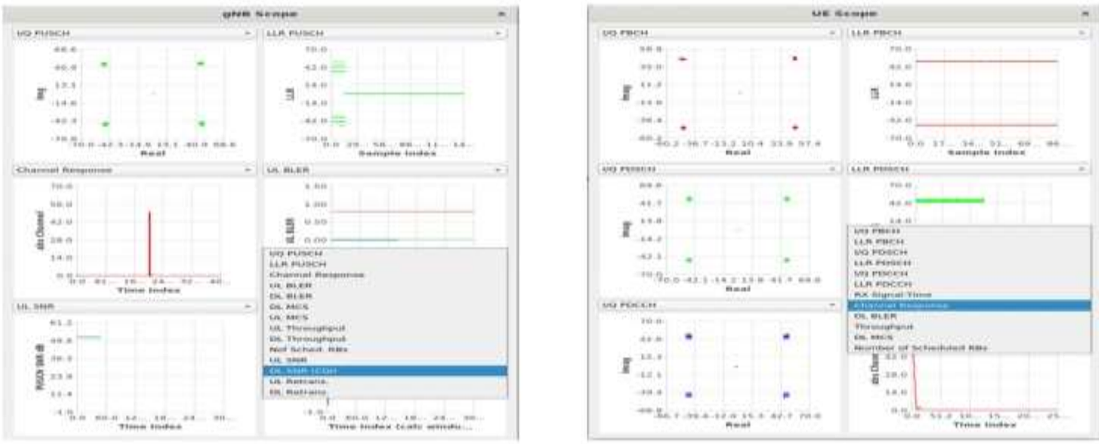
A. SETUP OF HARDWARE AND SOFTWARE

Our measuring setup included two UEs connected to a gNB. The 20.04 LTS operating system, which used the 5G-NTN protocol stack, was installed on general-purpose x64 computers running Ubuntu Linux for all three network components. Ettus X310 SDRs were used, and a PCI Express Interface was used to connect them to PCs. The OAI standalone was also installed by us. The 5G core network architecture (SA) of the gNB computer (5GC).

Figure 5 depicts the experimental study's reference architecture, which uses a 5G-NR link to link the OAI gNB and two OAI UEs. Every device was on the ground at a station in Neuberg, Germany. The actual over-the-air test of our NTN platform over SES's ASTRA 2F GEO satellite, located at 28.2° East, was conducted at this location as the measuring setting. The satellite created a single NTN cell for our European service zone and allowed seamless communication between the UEs and the gNB. For broadcasting in the UL, we converted the frequencies from the lower SDR frequency band to the Ku-band satellite transmission frequencies using a block upconverter.
In space, the GEO satellite served as an analogue repeater. It relayed the air interface between the OAI UE and OAI gNB by receiving and retransmitting 5G-NR signals. With a 400W high-power amplifier and a 7.6m Ku-band antenna, the hub station can achieve a G/T of 37.7dB/K and an equivalent isotropically radiated power (EIRP) of about 85dBW for saturation. For the 5G NR UL and DL, this configuration guaranteed a C/N of at least 15dB (Figure 6). Each carrier's allotted bandwidth for the 5G-NTN DL and UL was 5MHz. Figure 6 illustrates that the SDRs' local oscillator is a component of the in-band spectrum and has not been filtered.

TABLE 4. Parameter for over-the-satellite testing.

Parameter	Value
NTN band	Ku-band
Duplex mode	Frequency division duplex
$f_0^{Tx,UL}$	14 040.75 MHz
$f_0^{Tx,DL}$	14 034.75 MHz
Subcarrier spacing	15 kHz
Transmission bandwidth	5 MHz
Fast Fourier transform size	512
Sampling rate	7680 kSps
Round-trip delay	512.15 ms
Satellite terminal type	7.6 m Anchor Station
Modulation scheme	QPSK
Satellite	SES's ASTRA 2F @ 28.2° East (single beam)
R_{max}	679/1024
OH^{UL}	3/14
OH^{DL}	4/14
$N_{PRB}^{Bw,\mu}$	25
T_S^{μ}	0.000 071 428 571 428 571 43 s



(a) QT-based gNB scope (b) QT-based UE scope

FIGURE 4. QT-based graphical user interface to diplay key performance indicators (KPIs) for gNB and UE, developed during the 5G-GOA project. It visualizes various KPIs for the uplink and downlink in real time. Users can choose which KPIs they want to display.

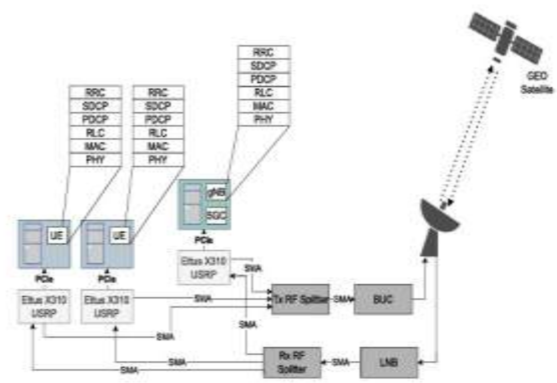


FIGURE 5. Architecture for the field trial. Our demonstrator includes the adapted protocol stack for OpenAirInterface.

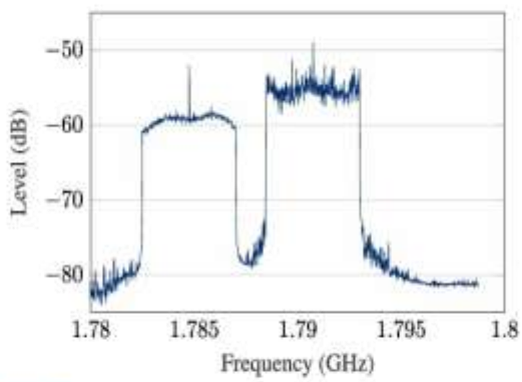


FIGURE 6. Transmitting and receiving satellite spectra from the gNB (left) and UE (right). A local oscillator can be seen in the spectra in both the gNB and the UE.

B. ESTIMATION OF PERFORMANCE

Equation 1 from TS 38.306 [19] was used as a baseline to estimate the maximum throughput (TP) for our experiment.

$$TP[bps] = Q_m R_{max}(1 - OH)\frac{N_{PRB}^{Bw,\mu} 12}{T_S^{\mu}} \qquad (1)$$

where OH is the overhead, µ is the SCS, NBw, µ PRB is the maximum RB allocation, Rmax is the coding rate, and Qm is the maximum supported modulation order. We investigated single-carrier QPSK MCSs with a modulation order of two.

This suggests that our TP was most impacted by Rmax (Table 5.1.3.1-1 in [19]) and OH for UL and DL, respectively.

We used a fixed QPSK MCS for the gNB configuration file.

V. RESULTS

A. TIMING ADVANCE ESTIMATION

In order to facilitate TA estimation of UE with Global Navigation Satellite System 155103 VOLUME
12, 2024 F. Volk et al.: 5G NTNs With OpenAir Interface: An Experimental Study Over GEO Satellites (GNSS) capabilities, the 3GPP standardisation bodies introduced system information broadcast 19 (SIB19). However, our proof-of-concept application was unable to exchange 5GNTN parameters via an interface between the satellite network operator's network control centre. We obtained the satellite's pre-calculated orbit parameters in two-line element (TLE) format directly from the satellite network operator. The orbit of a satellite is frequently represented using TLE data. It is made up of mean orbital components that, to within a few kilometres, accurately define an object's position in space.

The information is utilised in conjunction with particular analytical propagation models and is stored as TLE. By adding solar and lunar gravity, the SDP4 Orbit Propagator improves upon the SGP4. It is applicable to satellites that have an orbital duration of at least 225 minutes. A space object's position can be estimated using SDP4 to within one kilometre [20].

B. THE FIRST ATTACHMENT

The first step in processing a 5G SA connection is synchronising the UE with the gNB. This synchronisation process includes DL and UL synchronisation. DL synchronisation is followed by UL synchronisation. Our UE successfully received the DL synchronisation signals.

The UE then completed the RA operation using the estimated TA value. After synchronisation, our UE finished the RRC connection creation process and sent a registration request message to our 5GC for registration. After a successful 5GC registration, the gNB sent an RRC reconfiguration message to the UE. Finally, the UE completed the PDU session creation and was ready to transmit data through the PDU session.

C. EVALUATION OF PERFORMANCE

1) In this work, we measured the user datagram protocol's (UDP) maximum possible bandwidth on our 5G-NTN testbed using the open-source program iperf31. We ran our 5G-NTN testbed for MCS scores between 0 and 9. Figure 9 shows the predicted TP for UL and DL based on Equation 1 as well as the measured TP for UL and DL. We discovered that our 5GNTN testbed achieved the expected TP for each QPSK MCS. Additionally, we looked at typical transfer protocols' maximum Goodput (GP) (Table 6). Due to the congestion control technique, we initially observed slow TCP and fast UDP internet connections (Quic).

TABLE 6. Maximum goodputs of transport protocols.

	UDP	TCP	QUIC
Downlink (Mb/s)	4.00	3.90	3.90
Uplink (Mb/s)	4.45	4.35	4.20

2) Latency of the network

Using the Linux Ping command, Figure 10 shows the distribution of the measured network delay. Furthermore, it shows the time dispersion to establish connections with the Quic protocol, which was measured using qperf2. Figure 10 illustrates the lower threshold for the network's latency by displaying the Timing Advance (TA) value allocation as seen in Figure 7. Compared to the TA estimation, an additional 20 to 30 seconds of processing time were needed for a successful ping. In 658 to 670 seconds, we successfully connected using the Quic process. Our results show that the RTDs from our testbed are similar to those from commercial GEO satellite internet RTD providers [21], [22].

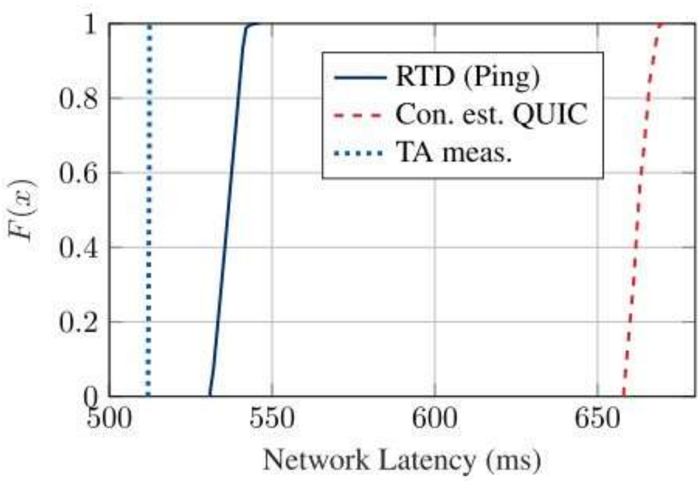


FIGURE 10. The empirical cumulative distribution function (ECDF), denoted as $F(x)$, represents the probability that the network latency assumes values less than or equal to the corresponding abscissa. The values for the time advance (TA) are the lower bound for the network latency. The ping-based round-trip delay (RTD) was within the expected range for geostationary satellites. Quick UDP internet connections (QUIC) were established shortly afterwards.

D. TWO UEs' VALIDATION

We developed a measurement procedure to measure the TCP GP using two UEs. After UE2, the first UE, sent a continuous stream of data for 30 seconds for 15 seconds, UE1 started sending data. The scheduling system ensured that both UEs received data, and we added a 15-second pause between the two transmissions.

E. APPLICATION VALIDATION

Using the in-lab performance analysis approach outlined in [8], we evaluated several satellite applications. Our user manual is available in PDF format [23]. The results show that the testbed can be used to evaluate a number of use cases over a 3GPP 5G-NR based satellite network.

VI. UPCOMING WORK

For example, we turned off the HARQ process in OAI to avoid "HARQ stalling." 3GPP advises increasing the number of HARQ processes from 16 to 32 for LEO satellites and disabling HARQ feedback for GEO satellites. Even though we only partially comply with the TA value computation, we take part in the preliminary testing of 3GPP-based 5GNTNs. According to 3GPP, the gNB is required to determine the common portion of the TA for the feeder link and deliver it to the UEs through PBCH (SIB19). The UE should compute the UE-specific part of the TA using its satellite trajectory data and GNSSbased position. Because our UE lacked GNSS capabilities and our gNB did not receive real-time satellite trajectories for determining the feeder link latency, we did not fully follow these recommendations. In order to get the satellite position information (ephemeris data), 3GPP considers a UE with GNSS capabilities and a SIB19 broadcast in their RAN2 working group. For the 5G-NTN, the RAN3 working group has suggested a number of enhancements, mainly for low-Earth orbit satellites and scenarios involving frequent user mobility. For example, Xn handover methods allow conditional handover between two gNBs. However, our method focusses on a relatively static environment in which handover is not necessary. The improvements that will be made in later work are

TABLE 9. Additional 3GPP release 17 5G-NTN enhancements.

Working Group	Impact
RAN1: Physical layer	Improvements to the hybrid automatic repeat request process (e.g., disabling of feedback messages)
RAN2: Access layer	**Control plane:** Tracking area management Idle/connected mode UE location services System information broadcast
RAN3: Access Network Architecture	Feeder link switch for LEO satellites Registration update and paging Network identity handling Cell relation handling Operations, administration, and maintenance

summarised in Table 9..

VII. SUMMARY

Supporting the applied research of publicly financed research institutions requires open research platforms that enable live demonstrations of the 5G-NTN standard. We kept a careful eye on the 3GPP Release 17 5G-NTN work items and adjusted the OAI software as needed. Long round-trip delays can be managed by compensating within various 5GNR protocol stack tiers thanks to our features. The end-to-end evaluation of our 5G-NTN implementations over a GEO satellite is summarised in this publication. Our results show that our testbed can control the varying latency of a GEO satellite and allow the UE to finish the first attachment. We also achieve the expected DL and UL throughput. Common end-user applications like web browsing, VoIP, and video streaming are demonstrated on our testbed. Our findings indicate that 5G-NTN testbeds with up to two UEs and one gNB, including 5GC, can be configured using our open-source software. The mobility aspects of satellites, which were not further investigated in this study, will be considered in future OAI implementations.

Acknowledgement

The opinions stated here do not represent the European Space Agency's official stance.

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