5G NON TERRESTRIAL NETWORKS

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Abstract— ***Non-Terrestrial Networks (NTN), powered by 5G and beyond, extend high-speed connectivity to remote areas using GEO and LEO satellites. While GEO supports fixed broadband and IoT, LEO enables low-latency, real-time applications. Direct-to-cellular (D2C) services enhance emergency communication, with future upgrades boosting data speeds. Defined by 3GPP, NTN integrates airborne and space-borne nodes to supplement terrestrial networks. With advancements in 3GPP Release-17 and Release-18, NTN is enhancing IoT, disaster response, precision agriculture, and infrastructure monitoring, ensuring seamless global coverage where terrestrial networks are limited.***

Keywords—NTN, 3GPP, GEO, LEO, Satellites, Gateways, D2C

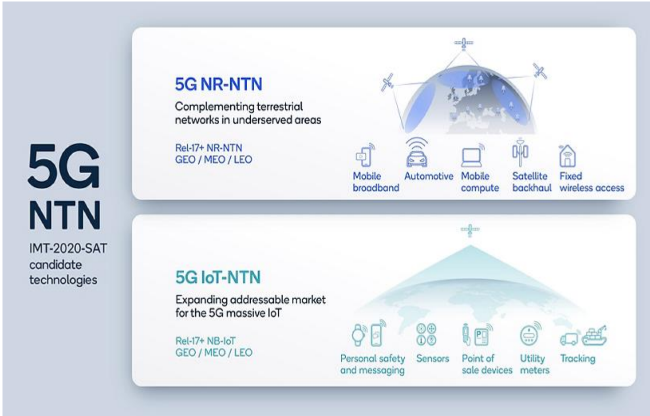
I. INTRODUCTION

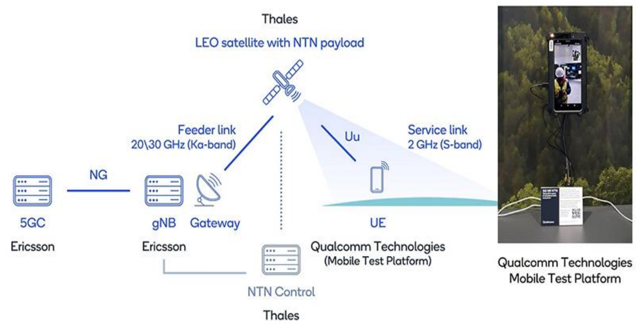
Non-Terrestrial Networks (NTN) are rapidly evolving, driven by the emergence of 5G, to provide high-speed wireless connectivity to remote and underserved areas using satellites. Current broadband services rely on GEO and LEO satellites, with GEOs (36,000 km altitude) supporting fixed broadband and IoT, while LEOs (<1,000 km altitude) offer lower latency and better link budgets.

NTN technology has significant potential for IoT applications, enabling real-time data collection in areas like precision agriculture, infrastructure monitoring, and disaster response. Direct-to-cellular (D2C) services are emerging, initially supporting messaging and emergency services over LEO networks, with future upgrades promising higher speeds. The 3GPP Release-17 utilizes sub-2GHz spectrum for tens of Mbps speeds, while Release-18 will introduce Ka-band spectrum, delivering speeds up to hundreds of Mbps for non-handheld devices, akin to Starlink.

Ultimately, NTN expands coverage beyond terrestrial networks, enhancing global connectivity, especially in rural and hard-to-reach regions.

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. An NTN-enhanced cellular network supplements a conventional terrestrial cellular network.





II. SYSTEM OVERVIEW

The integration of Non-Terrestrial Networks (NTNs) into 5G systems aims to provide global connectivity by incorporating satellite and aerial platforms alongside traditional terrestrial infrastructure.

Architecture of 5G NTN Systems

5G NTN architecture extends the terrestrial 5G network by incorporating non-terrestrial elements such as satellites and High-Altitude Platform Stations (HAPS). This integration facilitates ubiquitous coverage, especially in remote or underserved regions. The architecture can be categorized based on the placement of the gNB (Next Generation Node B) functions:

- **Transparent Payload Architecture**: Satellites act as relay stations, forwarding user signals directly to terrestrial gateways without processing.
- **Regenerative Payload Architecture**: Satellites perform on-board processing, handling gNB functions to manage user data before transmission to terrestrial networks.

These architectures enable seamless connectivity between terrestrial and non-terrestrial components, ensuring continuous service delivery across diverse environments.

Key Features of 5G NTN Systems:

- **Global Coverage**: NTNs provide connectivity in areas lacking terrestrial infrastructure, such as oceans, mountains, and rural regions.
- **Enhanced Reliability**: The integration of NTNs offers network redundancy, improving service reliability during natural disasters or terrestrial network failures.
- **Support for Diverse Applications**: NTNs facilitate various services, including broadband internet, emergency communications, and Internet of Things (IoT) applications in remote areas.

Challenges in 5G NTN Systems:

- **Propagation Delay**: The significant distance between satellites and user equipment introduces latency, affecting real-time applications.
- **Doppler Shift**: The relative motion between satellites and ground users causes frequency shifts, complicating signal processing and synchronization.
- **Power Constraints**: Satellites have limited power resources, necessitating efficient power management to ensure sustainable operations.
- **Spectrum Allocation**: Coordinating spectrum usage between terrestrial and non-terrestrial networks is complex, requiring regulatory harmonization to prevent interference.

Addressing these challenges is crucial for the successful deployment and operation of 5G NTNs, ensuring they complement terrestrial networks effectively.

Applications of 5g NTN Systems:

- **Ubiquitous continuity of 5G basic services:** NTN's extended coverage ensures seamless 5G services like mobile data, voice calls, and messaging across all terrains. This benefits both individuals and businesses by providing uninterrupted connectivity.
- **IoT revolution with 5G and NTN:** This integration can significantly enhance IoT capabilities. This supports more efficient data exchange, improved device interoperability and the creation of sophisticated IoT ecosystems, driving digital transformation across industries.
- **5G network backhaul support:** NTNs can serve as an effective backhaul solution for 5G networks. This can help extend network reach, improve capacity and ensure reliable connectivity even in remote or difficult-to-reach areas.

III. PROBLEM STATEMENT

With the growing need for global, high-speed connectivity, especially in remote and underserved areas, Non-Terrestrial Networks (NTNs) have become a vital extension of 5G infrastructure. By integrating satellite systems like LEO and GEO, NTNs offer wide coverage and support for emerging applications such as IoT, disaster response, and precision agriculture. However, the integration of NTNs into 5G poses key challenges, including high latency, Doppler shifts due to satellite mobility, limited power resources, synchronization issues, and complex network handovers.

Additionally, traditional modulation schemes, link budgets, and multiple access methods must be adapted to function efficiently in dynamic, high-altitude environments. Ensuring reliable, low-latency, and secure communication over NTNs requires addressing these challenges while maintaining quality of service and scalability.

The core problem is to develop an efficient, adaptive framework for 5G NTN integration that overcomes these technical limitations to deliver seamless, reliable, and cost-effective global connectivity.

IV. MOTIVATION AND CHALLENGES

5G NTN networks evolve in two variants: NTN-IoT and NTN-NR, catering to different use cases. NTN-IoT, which leads the market, extends IoT reach with global coverage on land, sea, and air, mainly operating in GEO and LEO orbits. As technology advances, NTN-NR will gain importance, directly connecting smartphones and 5G gateways with LEO satellites, enabling low-speed data, voice, and messaging services, and expanding the applications of non-terrestrial networks.

Until now, satellite communications were unthinkable for this type of use and were prohibitively expensive, but the emergence of new companies providing connection services through their own constellations of low orbit (LEO) satellites and their convergence with cellular connectivity for IoT have changed the rules of the game. These technologies arrive with the promise of ubiquitous IoT connectivity, guaranteed quality, easy maintenance, and low cost.

A number of challenges face NTNs and their applications, and additional obstacles will arise as these networks evolve.

The Space Environment : Space is the foremost challenge for NTNs. Once deployed, equipment is inaccessible. Furthermore, systems must operate in an extremely harsh environment with extreme temperatures and radiation. For successful performance, systems also need to provide consistent power generation and storage. Building mesh networks in space exacerbates these complexities by multiplying the chances for problems.

Size, Weight, Power, and Cost: Another concern is the physical limits of placing high-frequency RF and computing resources in the sky. Size, weight, power, and cost (SWaP-C) become issues when moving away from the GEO 20 tonners into more compact LEO satellites and HAPS platforms, and payloads must transform accordingly.

Connecting in constant motion: Non-terrestrial networks put some things, or perhaps everything in the network, in constant motion. NTN satellite and HAPS movements factor into connection setup, signal quality, and handovers. In a 5G NTN, gNodeB instances and parts of the radio access network (RAN) flying aloft add to the movement of any user equipment (UE) at the surface.

Choice of payload: The choice between transparent or regenerative payloads can completely change how the network organizes and the resulting signal routing. With LEO satellites in motion, all timing relationships are dynamic. At stake is the quality of service (QoS) user experience, primarily due to variable delays and complex handovers that can result in dropped connections.

Latency: The delay in signal transmission stems from the signal being sent between ground and satellite(s). Due to latency, an NTN does not currently support use cases demanding 3GPP Ultra Reliable Low Latency Communications (URLLC), such as telesurgery, which needs 1 ms with 99.99% reliability.

Security: While a distributed LEO satellite constellation spreads costs and risks across satellites, the hardware is vulnerable as it passes over unfriendly territories. National security needs exert demands for cyber protections and novel operations to protect infrastructure deployed in space. For example, the U.S. Space Force is tasked with this mission for all branches of military and government.

V. ORBITAL ISSUE

a) **High Transmission Delay :** The transmission delay varies across different satellite systems, with GEO satellites (35,786 km altitude) reaching up to 272.4 ms, NGEO at least 14.2 ms for 600 km LEO, MEO (10,000 km) up to 95.2 ms, and HAPS at least 1.526 ms—still significantly higher than terrestrial cellular networks at just 0.033 ms. These high delays impact real-time interactions between the base station and user terminals, especially in processes requiring multiple signaling exchanges, such as access, handovers, and HARQ, ultimately degrading user experience. This necessitates improvements or targeted redesigns of relevant protocol processes.

b) **Doppler Shifts :** Integrating LEO satellites into 5G NTNs poses challenges due to Doppler shifts from high relative velocities with user equipment. At altitudes of 600–1,400 km, LEO satellites cause Doppler shifts up to 50 kHz at 3 GHz and 720 kHz at 30 GHz, affecting signal synchronization. Their rapid motion leads to time-varying shifts, requiring adaptive frequency adjustments. 3GPP Release-17 uses GNSS chipsets for compensation, but these face issues like weak signals and interference. Despite transmitter pre-compensation, residual Doppler effects persist, necessitating additional receiver-side corrections for accurate synchronization.

c) **Peak to Avg ratio :** The peak to avg ratio in satellite communications is a key concern due to satellite payload limitations. Traditional satellite systems use single-carrier technology, whereas 5G NTNs rely on OFDM. This issue can be mitigated through techniques such as phased array antennas, where multiple beams share a power amplifier, minimizing differences between multicarrier and single-carrier methods. Additionally, peak clipping technology helps reduce peak-to-average ratios by capping signal peaks. Despite extensive discussions, 3GPP has retained the 5G waveform, leaving the optimization of peak-to-average ratio management to equipment vendors.

d) **Constellation - Hierarchail design :** The challenge is to transition from single-layer constellations to multi-layered, hierarchical designs with nodes at different altitudes. These nodes communicate via horizontal (same altitude) and vertical (different altitudes or terrestrial) links, improving flexibility and cost efficiency. For example, NB-IoT can use incomplete very LEO (vLEO) constellations for low-cost coverage while geostationary satellites ensure continuous core network connectivity.

VI. MODULATION AND CODING

For any communication technology, Modulation and Coding Scheme (MCS) defines the numbers of useful bits which can carried by one symbol. In contrast with 5G or 4G, a symbol is defined as Resource Element (RE) and MCS defined as how many useful bits can be transmitted per Resource Element (RE). MCS depends on radio signal quality in wireless link, better quality the higher MCS and the more useful bits can be transmitted with in a symbol and bad signal quality result in lower MCS means less useful data can be transmitted with in a symbol.

In other words, we can say MCS depends on Blocker Error Rate **(**BLER**)**. Typically, there is a BLER threshold defined that equal to 10%. To maintain BLER not more than this value in varying radio condition Modulation and Coding Scheme (MCS) is allocated by gNB using link adaptation algorithm. The allocated MCS is signalled to the UE using DCI over PDCCH channel.

- Modulation and Coding Scheme (MCS) defines the numbers of useful bits per symbols.
- Modulation = 2^n , Data rate = n/(n+k)
- MCS selection is done based on radio condition and BLER.
- MCS is change by gNB based on link adaptation algorithm.
- MCS information is provided to UE using DCI.
- 5G NR supports QPSK,16 QAM, 64 QAM and 256 QAM modulation for PDSCH.
- There are about 32 MCS Indexes (0-31) are defined and MCS Index 29,30 and 31 are reserved and used for re-transmission.
- 3GPP Specification 38.214 has given three tables for PDSCH MCS namely 64 QAM Table, 256 QAM Table and Low Spectral Efficiency 64 QAM Table.

64 QAM table may be used when gNB or UE is not supporting 256 QAM or in poor radio condition where 256 QAM table decoding is not successful and gNB needs to allocate QPSK order modulation.

256 QAM table may be used whenever 256QAM is to be allocated in very good radio conditions.

Low spectral efficiency **(**Low SE**)** 64 QAM table is suitable for applications which need reliable data transfer, e.g. applications belonging to the URLLC category. This table includes MCS which have low Spectral Efficiency i.e. a reduced coding rate which increase channel coding redundancy.

- gNB instructs the UE to select a specific MCS table using a combination of RRC signalling (IEs) and Physical layer signalling (RNTI).
- RRC signalling configure PDSCH-Config and SPS-Config parameter with the *mcs-Table* IE for a semi-static configuration which can be further modified using RRC signalling.
- Physical layer uses a dynamic selection of the RNTI which scrambles the CRC bits belonging to the PDCCH payload, e.g. switching between the C-RNTI and MCS-C-RNTI can influence the selection of the MCS table.

VII. LINK BUDGET DESIGN AND CONSIDERATIONS

Designing an effective link budget for 5G Non-Terrestrial Networks (NTNs) is essential to ensure reliable communication between satellites and user equipment (UE). Key considerations include:

1. **Satellite Orbit and Altitude:** Low Earth Orbit (LEO) Satellites: Operating at altitudes between 500 km and 2,000 km, LEO satellites offer reduced path loss and improved link budgets, leading to better signal quality and coverage. They also provide lower latency and higher data rates, enhancing communication responsiveness.

2. **Antenna Design:** Directional Antennas: Utilizing non-omnidirectional antennas can enhance the link budget by focusing energy on the satellite's orbital path, thereby improving signal strength and reliability.

3. **Atmospheric Conditions:** Environmental Factors: In tropical regions, heavy rainfall can significantly attenuate signals. Implementing diversity techniques, such as Multiple-Input Multiple-Output (MIMO) systems, can mitigate these effects and enhance signal-to-noise ratios.

4. **Interference Management:** Accurately estimating interference margins is crucial for downlink (DL) link budget calculations, ensuring that 5G communication systems maintain robust performance in the presence of potential signal disruptions.

By carefully considering these factors, engineers can optimize the link budget for 5G NTNs, ensuring efficient and reliable communication across diverse environments.

VIII. MULTIPLE ACCESS AND NETWORK ISSUES

In the context of 5G Non-terrestrial Networks (NTNs), multiple access techniques are crucial for managing the unique challenges posed by satellite and aerial communications. Several advanced multiple access strategies tailored for NTNs:

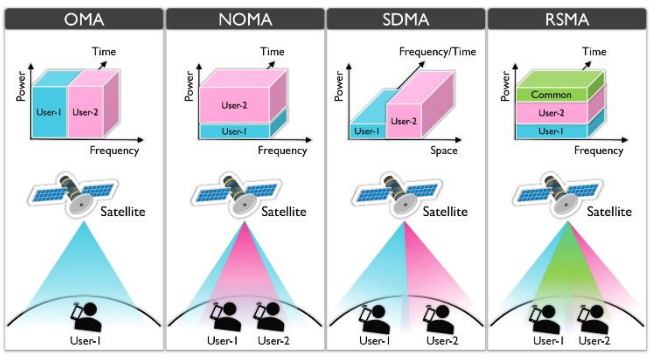
1. Spatial Division Multiple Access (SDMA): Spatial Division Multiple Access (SDMA) enhances spectral efficiency by leveraging MIMO and beam forming to direct signals toward users while minimizing interference. It treats interference as noise, improving efficiency without adding receiver complexity. However, SDMA is more effective in user-under loaded systems with perfect Channel State Information at the Transmitter (CSIT). In NTNs, user-overloaded scenarios and challenges like long round-trip delays (e.g., 250 ms for GEO, 30 ms for LEO) and high satellite mobility (~7.5 km/s for LEO) make perfect CSIT infeasible, limiting interference management effectiveness.

2. Rate-Splitting Multiple Access (RSMA): RSMA is a pivotal NGMA technique that divides user messages into common and private components. This division enables more efficient management of interference and resource allocation, making it particularly suitable for the dynamic environments of NTNs. By allowing partial overlap of user signals, RSMA enhances spectral efficiency and user fairness.

3. Non-Orthogonal Multiple Access (NOMA): NOMA allows multiple users to share the same frequency resources by differentiating their signals through power levels or unique codes. This approach increases the number of simultaneous connections and improves spectral efficiency, which is essential for the expansive coverage goals of NTNs.

4. Orthogonal Multiple Access (OMA): Traditional OMA techniques, such as Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA), allocate distinct time or frequency resources to users. While simpler, these methods may not fully utilize the available spectrum, especially in the high-demand scenarios typical of NTNs.

Integrating these advanced multiple access techniques into 5G NTNs is vital for achieving the global connectivity envisioned in future 6G networks. They address the inherent challenges of NTNs, such as long propagation delays, Doppler shifts, and dynamic network topologies, ensuring efficient and reliable communication.



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