BRIDGING THE DIGITAL DIVIDE

ONE CONNECTION AT A TIME

nuRAN WIRELESS

Demystifying LEO and its Impact on Rural Connectivity

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1 Demystifying LEO and its Impact on Rural Connectivity

1.1 Introduction

Presently, Low Earth Orbit (LEO) satellites and service providers are attracting much deserved attention. The general belief is that LEO satellites have arrived to eradicate the digital divide present in many countries. Even standardisation bodies like 3GPP are developing technical specifications to include LEO satellites as an alternate means to deliver mobile services, referred in the industry as "Non-Terrestrial Networks" (NTN). There is excitement and hype that the digital divide will soon become a distant memory, and the longstanding battle to connect everyone everywhere will finally be won.

This paper aims to provide a realistic perspective of LEO satellites and its impact on communication particularly in unserved and underserved areas. We are excited about what the future holds with LEO, but cognisant and wary of the many challenges and the long road that lies ahead. LEO satellites are not a silver bullet, but rather another weapon in the connectivity armoury. The paper begins with a summary of LEO satellites and service delivery models. Subsequently, challenges surrounding LEO satellites are addressed and where possible compared to terrestrial networks. Finally, conclusions are drawn on the impact of LEO to closing the digital divide.

1.2 LEO Satellites

Low Earth Orbit (LEO) satellites, positioned between 300 and 1,400 km above Earth's surface, employ vast constellations of satellites to achieve global coverage. Compared to geostationary satellites (35,000 km), LEO satellites operate closer to Earth, resulting in lower latency for data transmission. LEO constellations range from hundreds to thousands of satellites, traveling at speeds of approximately 7.5 km/s and completing their orbits every 90 to 110 minutes. Each satellite has a communication window that lasts 5 to 15 minutes and occurs 6 to 8 times a day. Frequent satellite handovers are thus required to sustain uninterrupted communication. Ground stations ensure efficient control and operation of LEO satellites and interconnect non-terrestrial networks with terrestrial networks. These are situated at either strategic locations around the globe or in the country where the services are delivered.

1.2.1 Service Offering

LEO satellite services can be broadly categorised into two distinct offerings:

- Satellite-To-Dish: This encompasses the traditional satellite service model where connectivity is beamed to a specific location and then distributed among inhabitants using other access technologies (e.g. Wi-Fi). NuRAN can take advantage of this service offering to augment or replace geostationary satellite capacity with higher throughputs and low latency capacity. This service delivery model fosters the growth of numerous satellite providers, thereby intensifying market competition. This proliferation positively impacts the price of satellite capacity (i.e., price per Mbps), making connectivity more affordable and accessible to end-users. Many LEO service providers have opted for this approach.
- Satellite-To-Phone: Representing a paradigm shift in satellite communication, this innovative model allows mobile phones to directly access services from satellites, effectively transforming the satellite into a network access point and not just a transmission link. This novel method, viewed as a threat to established rural mobile network players like NuRAN, is the focus of this paper as we delve into the disruptive potential and implications of this technology.

The table below lists the more prominent LEO service providers and their planned service delivery model. Most notably, two LEO service providers have opted for the Satellite-To-Phone service delivery model, deploying a mobile site or radio head in space, marking a strategic divergence from the traditional Satellite-To-Dish approach.

LEO Provider	Orbit Height (Km)	Latency (ms)	Satellite-To-Dish	Satellite-To-Phone	Satellite Life (Years)
AST SpaceMobile	725	< 50	No	Yes	~ 5
Lynk Global	500	< 50	No	Yes	~ 5
OneWeb	1,200	< 50	Yes	No	~ 5
Starlink (SpaceX)	550	< 50	Yes	Trying	~ 5
Kuiper (Amazon)	600	< 50	Yes	No	~ 5
Lightspeed (Telesat)	1,300	< 50	Yes	No	~ 10

The question on everyone's mind: how will Satellite-To-Phone service providers impact terrestrial rural network players and to what extent?

1.2.2 Communication Services

This paper collectively refers to Mobile and Broadband services as Communication Services. Mobile services are delivered by Mobile Network Operators (MNO) while traditional broadband services are delivered by Internet Service Providers (ISP). From a user's perspective, they appear the same, but the underlying infrastructure, concession and spectrum resources is different. Recent mobile technologies, such as a 4G and 5G deliver Mobile Broadband Services (MBB), not to be confused with ISP Broadband services.

The role satellite has played and continues to play is to facilitate the delivery of mobile and broadband services to underserved areas when traditional infrastructure is limited or non-existent. The way satellite is delivering this connectivity is evolving particularly for Satellite-To-Phone service offering.

1.2.3 Global Connectivity

Global connectivity is not only about providing coverage to every corner of the Earth but doing so in an affordable way. Service availability in rural areas does not automatically translate into service usage, which is the end goal. Readers should understand the difference between "providing global connectivity" and "bridging the digital divide". Both phrases are often used interchangeably but have very different connotations. Connectivity is instrumental to reducing the digital divide, but ultimately can only be solved by offering end-users access to affordable, relevant, and enduring services,

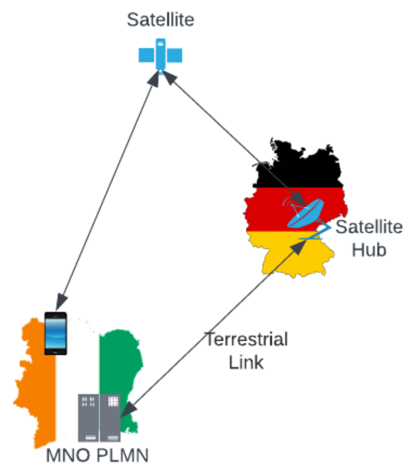
LEO satellites can provide global coverage, promising to deliver connectivity to remote and underserved areas. However, large satellite constellations (in the hundreds or thousands) must be launched over a period of several years to reach this milestone. Until said time, coverage will be limited to specific orbits and countries. Before satellite services can be offered in LEO covered countries, landing rights must be sought and approved by local authorities, typically a long drawn bureaucratic process. Global coverage will unequivocally become a reality, but not for many years.

A key success factor to delivering connectivity to rural areas is doing so at the right price. A country's economic situation and spending power of its inhabitants weighs heavily on service uptake and demand, particularly for impoverished areas. Delivering satellite services to rural England is a very different ball game to delivering services to rural Africa. For some African countries, the Average Revenue Per User (ARPU) in rural areas can be as low as $0.80 USD per month. A "one size fits all" model does not work, in large part applicable to satellite providers as most of the infrastructure to deliver services is the same.

1.2.4 Regulatory Concerns

Satellite-To-Dish and Satellite-To-Phone service delivery models both require landing rights to operate in a country, much like other satellite service providers. Managed by the regulator, these rights are costly and time consuming to obtain.

Another important consideration is the location of ground stations. LEO satellite architectures not able to install ground stations in the country where services are delivered will come under regulatory scrutiny for security and privacy reasons due to cross-border information exchange. This may prevent, or at a minimum, delay the entry of LEO services in some countries.



Satellite-to-Phone services providers deliver connectivity using mobile frequency bands. Much like NAAS, the LEO service provider must sign an agreement with a mobile network operator to use its spectrum and obtain a valid operating license from the regulator. This is in addition to the landing rights mentioned above. Lastly, Satellite-To-Phone connectivity is a more complex variant of the NAAS business model not considered in the regulatory framework of most countries, thus adoption will prove more challenging.

1.3 Satellite-To-Phone Service Limitations

This section highlights the main technical challenges to delivering mobile services from a "site" in space when compared to traditional terrestrial sites. The high altitude of satellites offers great coverage but has an impact on its capacity and performance.

1.3.1 Balancing Coverage and Capacity

In the realm of Satellite-To-Phone services, various challenges arise from the intricate interplay between coverage, capacity, and the inherent properties of satellite communication.

- Coverage Dynamics: Achieving comprehensive coverage is the foundational step in delivering mobile services via satellite. The extent of coverage directly impacts the number of users a satellite site can serve. However, as connections and traffic increase over time, the available capacity is distributed among more users, affecting access and service quality. This dynamic allocation of resources poses a significant challenge, necessitating strategic management to ensure satisfactory user experiences amidst growing demand.

- Capacity Enhancement Strategies: To address the evolving demands of users and optimize network performance, several strategies are employed to augment capacity. Notably, the implementation of smaller cells with tight frequency reuse emerges as a key approach. By subdividing large cells into clusters of smaller cells, each equipped with its own resources, significant capacity enhancements can be achieved. Additionally, advanced user multiplexing techniques, spanning time, frequency, and space dimensions, further optimize capacity allocation and spectral efficiency.
- Influence of Satellite Height on Coverage: The altitude of the satellite directly impacts the size of its coverage footprint. Despite efforts to deploy highly directional transmissions, such as those facilitated by small antenna beamwidth or beamforming, the shadows cast by these transmissions remain substantial. Consequently, deploying small "cells" in space becomes challenging due to the constraints imposed by satellite height.
- Limitations on Coverage Beam Size: While striving to optimize capacity and spectral efficiency, there exists a fundamental limit to how small the coverage beam of a satellite site can realistically be. This constraint is compounded by the primary virtue of satellites, which is to provide expansive coverage across vast geographic areas. Thus, stakeholders must navigate the delicate balance between coverage footprint size and the inherent limitations of satellite-based communication systems.

1.3.2 LEO Spatial Multiplexing

Massive-MIMO technology, or Massive Multiple Input Multiple Output, is a cutting-edge method utilized to augment user data rates and cell capacity by exploiting spatial multiplexing of users and transmissions. While it has seen significant development and implementation in terrestrial communications infrastructure, its adaptation for satellite communications remains a challenge. This is primarily due to several impediments unique to satellite systems.

The foremost obstacles hindering the deployment of Massive-MIMO in satellite communications include the considerable propagation delay inherent in satellite transmissions, the relatively short coherence time, and the substantial atmospheric losses experienced during signal transmission. These factors collectively obstruct the reception of instantaneous channel state information (iCSI), which is crucial for the effective implementation of Massive-MIMO technology.

Consequently, satellites are unable to fully leverage the benefits of Massive-MIMO, resulting in limited capacity compared to their terrestrial counterparts. Despite the advancements in terrestrial communication systems, the adaptation of Massive-MIMO for satellite communication networks necessitates innovative solutions to overcome the inherent challenges posed by the space environment.

1.3.3 Maximise Spectrum Usage

Maximising the utilisation of spectrum resources is paramount due to its intrinsic value and limited availability. Over the years, mobile technologies have evolved to become increasingly spectrally efficient, allowing them to transmit more information within a given bandwidth. This evolution is essential to meet the escalating demands for user connections, required throughputs, and data volumes in modern communication networks.

Several factors contribute to enhancing capacity within communication networks. These include employing small cell sizes, implementing frequency reuse strategies, and utilizing multiplexing techniques. Additionally, one effective method to increase capacity is to use multiple frequency layers, effectively adding more spectrum to a site.

In urban environments where the demand for mobile data is high, it's common to deploy multiple technologies across various frequency bands to efficiently manage traffic demands. Conversely, rural sites presently experience lower traffic demands, but will escalate as communication needs evolve over time.

While terrestrial sites can readily accommodate technology upgrades, support multi-band operations, and facilitate flexible carrier bandwidths, the same advancements are more challenging to implement in satellite communication systems. Terrestrial infrastructure benefits from easier access to technological upgrades and the ability to support a broader range of frequency bands, providing greater flexibility to adapt to changing demands in communication networks.

1.3.4 Inherent Propagation Delay

Maximizing site capacity in mobile broadband technologies (MBB) involves dynamically tracking fluctuating radio frequency (RF) conditions to efficiently schedule users on the most suitable resources during each transmission opportunity, typically referred to as Transmission Time Interval (TTI). For instance, HSPA (3G) systems perform scheduling every 2 milliseconds, while LTE (4G) systems do so every 1 millisecond.

However, in Low Earth Orbit (LEO) satellite communication systems, inherent propagation delays are typically greater than the scheduling rates of MBB technologies. This poses a significant challenge as it limits the ability to schedule users effectively, thereby reducing total site connections, user throughputs, and overall cell capacity. Moreover, the scheduler residing at the satellite site further exacerbates this issue, particularly in the uplink transmission direction.

Additionally, high subscriber density within the coverage footprint of a satellite can have adverse effects on service access and performance. As the number of users increases within the satellite's coverage area, the available resources become congested, leading to potential degradation in service quality, increased latency, and decreased throughput for individual users.

Addressing these challenges requires innovative approaches to optimise scheduling algorithms, mitigate propagation delays, and manage subscriber density effectively. Strategies such as advanced beamforming techniques, adaptive resource allocation, and intelligent interference management can help enhance the efficiency and capacity of LEO satellite communication systems, enabling them to better meet the demands of modern mobile broadband services.

1.3.5 Latency and Jitter

Latency and jitter are critical metrics that significantly impact the quality of service, particularly for real-time applications such as Voice over Internet Protocol (VoIP) and video conferencing.

Latency refers to the time taken for packets to travel between two points, while jitter represents the variation in latency between packet arrivals. Both latency and jitter can adversely affect real-time services, where timely delivery of packets is crucial for maintaining communication quality.

Low Earth Orbit (LEO) satellite networks offer improved latency compared to Geostationary Earth Orbit (GEO) satellites due to their closer proximity to Earth. However, LEO latency is still higher than that of terrestrial networks. On average, LEO latency is around 50 milliseconds, approximately 12 times lower than GEO satellites. Despite this improvement, it's important to note that real-time applications may still experience delays compared to terrestrial connections.

Real-time services, such as VoIP and video conferencing, are particularly sensitive to latency and jitter. These services do not typically involve packet retransmissions or reordering, making timely delivery more crucial than delivery integrity. High jitter levels can result in packets being lost, arriving out of order, or failing to arrive on time, leading to degraded call quality and user experience.

The non-stationary nature of satellites, coupled with the need for handovers between satellites as they orbit the Earth, can further increase jitter. These handovers introduce additional delays and variations in latency, impacting the quality of voice and video calls transmitted over satellite networks.

To mitigate the impact of latency and jitter on real-time services, satellite communication systems must employ efficient routing algorithms, adaptive buffering mechanisms, and prioritization schemes to ensure timely delivery of packets and minimize variations in latency. Additionally, advancements in satellite constellation design and satellite positioning technology can help reduce handover-related jitter, further improving the overall quality of service for real-time applications.

1.3.6 Received Signal Strength

When connecting to a Low Earth Orbit (LEO) satellite, all phones experience a uniform set of conditions due to the satellite's distance and the characteristics of satellite communication:

i. Same average received signal strength: Phones connected to a LEO satellite typically encounter nearly identical average received signal strength. This uniformity arises because all phones are essentially at the same distance from the satellite. Furthermore, the slow tracking of radio frequency (RF) conditions ensures minimal variation in signal strength among connected devices.

ii. Similar scheduler treatment: The scheduler within the satellite network treats all connected phones similarly in terms of receive and transmit power levels. This approach limits scheduling decisions primarily based on buffer occupancy and the subscriber profiles defined by the Mobile Network Operator (MNO). Consequently, phones experience comparable treatment in terms of resource allocation and prioritization.

iii. All phones at the cell edge: In a LEO satellite network, all phones effectively operate at the cell edge due to the satellite's orbiting nature. Consequently, phones typically require higher uplink transmit power to maintain connectivity. However, this increased power consumption poses a significant challenge, particularly in areas with limited electrical infrastructure, where preserving battery life is crucial.

iv. Less power control headroom: The uniformity of signal strength and the prevalence of phones operating at the cell edge result in reduced power control headroom. This limitation makes it challenging to overcome deep signal fades, particularly in indoor environments where network usage is prevalent. As a result, indoor coverage becomes an issue, affecting the overall user experience and network performance.

Overall, while connecting to a LEO satellite offers advantages such as reduced latency and improved connectivity in remote areas, it also presents challenges related to uniform signal conditions, power consumption, and indoor coverage limitations. Addressing these challenges requires innovative solutions in satellite network design and optimization to ensure reliable and efficient communication for all connected devices.

1.3.7 Site Interworking

Ensuring seamless integration and operation between satellite and terrestrial sites is crucial in modern communication networks, but it poses several challenges that must be carefully managed:

i. Coverage overlap management: To prevent unnecessary interference, meticulous planning is required to manage coverage overlap between satellite and terrestrial sites. Proper coordination of coverage areas helps optimize resource utilization and minimize potential interference issues.

ii. High-power transmission from satellite-connected devices: Mobile phones connected to satellite sites may transmit at higher power levels, leading to increased noise levels for nearby terrestrial sites operating on the same carrier frequency. This elevated noise can degrade the performance and capacity of interference-limited technologies like 3G and 4G, hindering overall network performance.

iii. Complex interworking between satellite and terrestrial networks: Achieving seamless mobility and handover between satellite and terrestrial networks in both idle and connected modes present a significant challenge. The transition between these networks requires intricate interworking mechanisms to maintain uninterrupted connectivity for users as they move between coverage areas.

iv. Interference coordination and resource allocation: Managing interference coordination and resource allocation between satellite and terrestrial sites is inherently complex. Both types of networks exhibit different responsiveness to radio frequency (RF) channel variations, making it challenging to synchronize and optimize resource usage effectively. Coordinating frequency reuse, power control, and beamforming strategies becomes essential to mitigate interference and maximize network performance.

Addressing these challenges demands collaborative efforts among satellite and terrestrial network operators, along with advancements in network planning, optimization, and interworking technologies. By implementing robust interference management mechanisms and efficient resource allocation strategies, it's possible to enhance the coexistence and interoperability of satellite and terrestrial networks, ensuring seamless connectivity and optimal performance for users across diverse coverage areas.

1.3.8 Other Considerations

Deploying and maintaining Low Earth Orbit (LEO) satellite networks entail several significant considerations:

i. Limited satellite lifespan: LEO satellites typically have a lifespan of around 5 years. Consequently, replacement planning is crucial and can be costly. The need to continuously replace aging satellites adds complexity and expense to the operation of LEO satellite networks.

ii. High deployment costs: The cost of deploying LEO services is substantial for several reasons. Firstly, launching numerous satellites into space requires significant financial investment. Additionally, establishing ground stations worldwide to support satellite operations adds to the expense. Furthermore, the equipment required for Very Small Aperture Terminal (VSAT) communication with LEO satellites is expensive, contributing to the overall high deployment costs.

iii. Uncertain service pricing for Satellite-to-Phone services: Determining the pricing for Satellite-to-Phone services poses challenges for Mobile Network Operators (MNOs). It remains unclear whether existing terrestrial tariffs will apply to satellite services or if higher "roaming" type prices will be implemented to account for the substantial initial investment in satellite infrastructure. This uncertainty complicates pricing strategies for MNOs and may impact consumer adoption of satellite-based communication services.

iv. Multiple country coverage adds another layer of complexity: LEO satellites must support a wide range of mobile frequency bands, each with potentially different allocations per country. As a result, designing the radio units for LEO satellites to accommodate multiple frequency bands and regulatory requirements is significantly more complex.

v. Disparate business models: Mobile Network Operators (MNOs) face difficulties in extending coverage to rural areas due to the distinct nature of the business and operational models in these regions. The cost-effectiveness and profitability of deploying and maintaining infrastructure in rural areas often deter MNOs from undertaking such endeavours independently. As a result, MNOs seek partnerships with service providers capable of supporting the complexities associated with rural coverage expansion.

1.4 Conclusions

Satellite providers play a pivotal role in extending coverage to rural areas. However, as highlighted earlier, global connectivity is not only about coverage, but about also delivering capacity and affordable services. Making communication services available in rural areas does not translate into sustainable usage, a key requisite to bridging the digital divide.

NuRAN believe satellite and terrestrial networks are mostly complementary. Satellite's forte is coverage and terrestrial can deliver substantially more capacity. This cooperation will continue and become closer. Our take on the different satellite service models is as follows:

- NuRAN views *Satellite-to-Dish* providers as another backhaul option for the NAAS business model, offering a lower latency and higher throughput alternative to GEO providers. Increased sector competition will help make satellite capacity more affordable, positively impacting our NAAS offering.
- NuRAN views *Satellite-to-Phone* providers as complementary to our NAAS business model rather than a competitor. While NuRAN focuses on covering low-income rural communities, Satellite-To-Phone services primarily serve higher-income nomadic users. Our target segments are different allowing us to meet diverse connectivity needs of different user groups in rural areas.

The digital divide is a moving target as communication needs evolve. What solves the problem today, may not suffice tomorrow. The demand for mobile services continues to grow in terms of connections and the capacity and throughputs required to support diverse users and applications. This expansive market can cater for many communication service providers with a variety of solutions tailored for different regions and demographics.

Affordable global connectivity demands cooperation between public and private sectors, as well as national and international organisations. No single organisation can solve the digital divide. Cognisant of this fact, NuRAN welcomes new players, new innovations, and new partnerships to play their part in connecting our world and bridging the digital divide.