Very-Low-Earth-Orbit Satellite Networks for 6G

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Abstract

With the breakthrough of advanced satellite launching and manufacturing technologies in recent years, both the academia and industrial communities are making considerable efforts to study mega constellations for Very-Low-Earth-Orbit (VLEO) satellites. The non-terrestrial network (NTN) is widely believed to be a part of the 6G network. In this paper, the vision for the evolution of VLEO satellites-based NTN towards 6G is proposed, as well as the technical challenges and potential solutions.

Keywords

VLEO, mega constellation, 6G, NTN

1 Introduction

The idea of Very-Low-Earth-Orbit (VLEO), which is at an altitude of around 350 km, has the potential to change the paradigm for the Internet because it is much lower than the traditional low Earth orbit (LEO) of 600 km to 1200 km or geostationary Earth orbit (GEO) of 35768 km. Accordingly, communications based on mega VLEO constellations are envisioned owing to attractive features such as low transmission delay, smaller propagation loss, high area capacity, and lower manufacturing and launching cost when compared with traditional LEO or GEO satellites. All these features will contribute to wider global utilization.

Satellite-based communications are believed to be an important part of 5G-Advanced and 6G by the global communication ecosystem. The 3rd Generation Partnership Project (3GPP) [1] has officially started researching on integrating satellite communications with 5G New Radio (NR) techniques titled "non-terrestrial network (NTN)." The study item (SI) of NTN (Release 14 to Release 16) identifies NTN scenarios, architectures, basic NTN issues and related solutions, and 12 potential use cases by considering the integration of satellite access in the 5G network including roaming, broadcast/multicast, and Internet of Things (IoT) [2-4]. In Release 17, the first work item (WI) of New Radio Non-terrestrial Network (NR-NTN) and Internet of Things Non-terrestrial Network (IoT-NTN) were approved at the end of 2019. NR basic features will be supported by both regenerative and transparent satellite systems in Release 17 to Release 19. 6G NTN will begin from Release 20 and more enhancements and new features will be discussed, including but not limited to support for integrating terrestrial networks (TN) and NTN and improved spectral efficiency compared to 5G and 5G-Advanced NTN. NTN with ultra-dense VLEO constellation will be a part of the 6G network and play an essential role in ensuring extremely flexible communication access services.

To achieve successful commercialization of VLEO-based NTN, new usage scenarios and applications need to be explored and a few technical challenges need to be addressed. A comprehensive discussion of the vision and challenges of VLEO-based NTN for 6G will be presented in this paper. The remaining parts of this paper are organized as follows. Section II introduces the driving factors and motivations of VLEO-based NTN networks according to the latest progress from the industrial community. Section III summarizes the usage scenarios and applications that mostly have gained the consensus of both the academia and the industry. Section IV identifies the challenges, and the potential solutions that might require a long-term effort for developing a competitive VLEO-based NTN. Section V draws the conclusion.

2 Driving Factors and Motivations

2.1 Requirements

Non-terrestrial communications such as satellite communications will be leveraged to build an inclusive world and enable new applications in a cost-effective way. The wireless coverage is expected to expand coverage from 2D "population coverage" on the ground surface to the 3D "global and space coverage." Integrating non-terrestrial and terrestrial communications systems will achieve 3D coverage of the Earth. They will not only provide communications with broadband and wide-range IoT services around the world, but also provide new functions such as precision-enhanced positioning and navigation and real-time earth observation.

With the development of new High-Throughput Satellite (HTS) as well as Non-Geostationary-Satellite Orbit (NGSO) systems such as the Medium-Earth-Orbit (MEO) system O3b and many proposed LEO and VLEO systems, such as Oneweb [5], Starlink [6], and TeleSat [7], it is expected that the cost will become much lower, the access capabilities will increase, and time delay of satellite connections will be reduced by VLEO constellations. SpaceX's Starlink project has launched over 1900 satellites by the end of December 2021, which made this company the world's largest satellite communications operator [8]. The decreasing cost of the satellite manufacturing and launching service is making the advent of huge fleets of small satellites in low earth orbits a reality. In addition to bridging the "digital divide", the role of satellite communications in 2030 and beyond is perceived to be pivotal in ensuring data connectivity to both fixed and mobile users.

2.2 Benefits of Integrating TN and NTN

Compared with the cellular network, the satellite communications service still calls for dedicated and expensive user terminals, which are out of reach of common users. A fundamental integration of TN and NTN will change the status quo and significantly improve user experience. With this integration, the satellite communications industry can fully utilize the fast development and economies of scale of the cellular industry, thus reducing the cost of terminals and the service price to more attractive levels. By achieving unified design of TN and NTN, the barrier among different satellite systems will also be eliminated, allowing users to freely roam among terrestrial networks and non-terrestrial networks of different operators.

3 Usage Scenarios and Applications

The VLEO-based NTN is expected to provide couples of usage scenarios and applications, as shown in Figure 1.

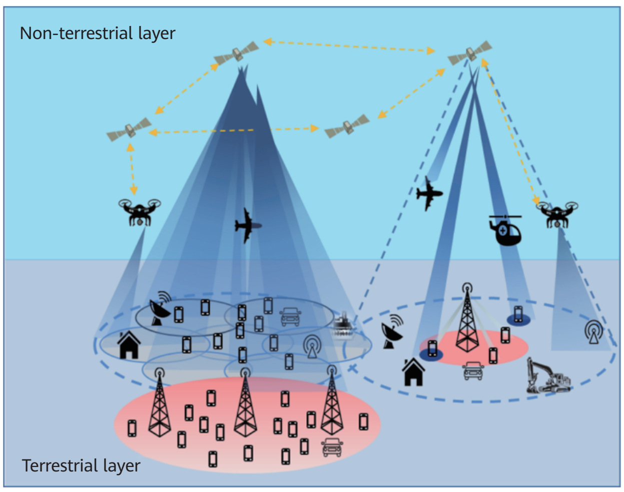


Figure 1 Usage scenarios and applications

3.1 Extreme Coverage

Today, almost half of the world's population lives in rural and remote areas that do not have basic Internet services. Non-terrestrial networks can provide affordable and reliable connectivity and broadband services for areas where telecommunications operators cannot afford to build terrestrial networks. By using non-terrestrial network nodes, such as satellites, unmanned aerial vehicles, and high-altitude platforms, non-terrestrial networks can be flexibly deployed, connecting people through various devices such as smartphones, laptops, fixed-line phones, and televisions.

3.2 Mobile Broadband for the Unconnected

Current commercial satellite communications systems have low transmission rates and high costs. In addition, satellite mobile phones are not integrated with the terminal equipment of the traditional terrestrial cellular network, and people will have to use two different mobile phones to access the satellite network and the cellular network respectively. In the future, we believe satellites can directly connect to mobile phones, providing broadband connectivity, with data rates similar to those of cellular networks in remote areas. For example, the user data rate should be able to reach 5 Mbit/s for download and 500 kbit/s for upload.

3.3 Broadband Connection on the Move

People should be able to access the Internet anytime, anywhere, no matter what kind of transportation they take. Take the air traffic scenario for example. In 2019, over 4 billion people traveled by aircrafts, which means almost 12 million people fly somewhere every day [9]. Most of them have no Internet connection during the flight or experience Internet access at very low speed. Future communications systems should provide MBB experience connections for all aircraft passengers.

3.4 Wide-Range IoT Services Extended to Unconnected Locations

Currently, IoT communications are implemented based on cellular network coverage. However, cellular-based IoT communications cannot guarantee connection continuity in many scenarios. In the future, IoT devices should be able to connect and report information anytime, anywhere. As a result, it will become easier to use NTN to collect information, such as the status of Antarctic penguins, the living conditions of polar bears, and animal and crop monitoring, from remote and uninhabited areas.

3.5 High-Precision Positioning and Navigation

In the future, most cars will have the capability to connect to the terrestrial network. However, the terrestrial network may not be able to provide high-quality vehicle-to-everything (V2X) services for users in remote areas. The integrated network can implement high-precision positioning and navigation and improve the positioning accuracy from meters to centimeters. On this basis, automatic driving navigation, precision agriculture navigation, mechanical construction navigation, and high-precision user positioning services can be provided.

3.6 Real-Time Earth Observation and Protection

With the development of remote sensing technology and the fast deployment of mega constellations, the future remote sensing technology will ultimately be in real time and feature high resolution. With these two significant features, earth observation can be introduced to more scenarios, such as real-time traffic dispatch, real-time remote sensing maps available to individual users, high-precision navigation combined with high-resolution remote sensing and positioning, and quick response to disasters.

4 Challenges and Solutions

To realize the usage scenarios and applications listed earlier, critical challenges and possible solutions are identified in this section, as enablers to a fully integrated network with TN and NTN for the 6G era.

4.1 Integrated Network Architectures

To provide unified services with a single device, new integrated network architectures composed of both TN and NTN need to be proposed. However, several challenges need to be overcome to realize a truly integrated network.

- The integrated network is in general a 3D heterogeneous network, with each layer having different coverage ranges and link quality. It is critical to coordinate each layer in the network to achieve unified network access. In addition, user equipment (UE) should have the flexibility to communicate with the most appropriate layer based on its own capability and context.
- A wide range of services with different quality of service (QoS) requirements will be supported by the integrated 6G network. However, the resources in the integrated network must exhibit a high level of heterogeneity. The resource availability for multiple services will vary over time, as each segment may dynamically allocate resources with high priority to support legacy services [10].
- The global span of an integrated network calls for reliable control anywhere, anytime. This typically requires a large number of ground stations to be deployed all over the world, which induces high complexity and increases expenditure. The end-to-end delay can be quite large since core network functions are implemented at very few sites on the ground and inter-plane inter-satellite link (ISL) communications are rather limited due to visibility and velocity constraints.

The following are potential technical solutions to overcome the preceding challenges.

- 3D UE-centric cell-free communication [11] is a promising solution for the integrated network. With UE-centric methodology, the cell boundaries can be eliminated efficiently. This leads to interference-free and reduced handover communications in scenarios with many heterogeneous access points. On the other hand, spatial multiplexing for cell-free communications means that the beams from multiple nodes, e.g., satellites and terrestrial base stations, can be resolved by using different phase gradients on the receiving array. It is thus possible to serve any location on the ground from multiple distinct sites and directions by fully exploiting the space-air-ground dimensions of the entire network.
- Network slicing enables multiple logical networks to run as independent tasks on a common shared physical infrastructure. Each network slice represents an independent virtualized end-to-end network and allows operators to perform multiple functions based on different architectures. As a consequence, a set of customized services with distinct QoS levels can be

provisioned by deploying multiple isolated and dedicated network slices on top of the integrated network.

- A hierarchical control framework with very few ground stations and GEO satellites is used to achieve global network control, while MEO satellites and LEO/VLEO satellites with ISL capabilities are used for regional and local control. The concept of a space-based core network can be exploited to facilitate global control and reduce propagation delay. For example, some core network functionalities, e.g., user plane function (UPF) and access and mobility management function (AMF), can be placed onboard satellites, so that both control messages and UE traffic are not required to traverse to ground stations with many hops.

4.2 Air Interface Technologies

LEO/VLEO constellation will be an important component of 6G networks. The capacity density at each location on Earth can be used to understand the service capability of a constellation. Take Starlink "Gen2" constellation (including about 30000 satellites) [12] for instance. The peak average capacity density after full deployment is in the middle-latitude area, which is about 3.6 Mbit/s/km^2, as shown in Figure 2.

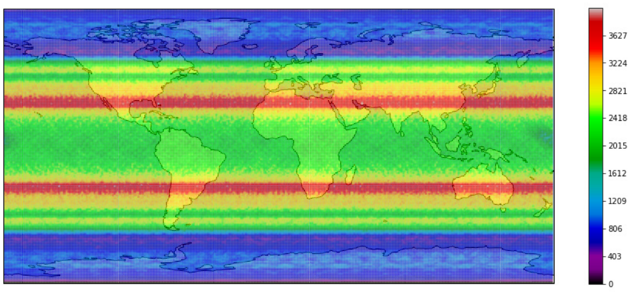


Figure 2 Starlink "Gen2" capacity density

The peak average capacity density is still very low compared with that of cellular services although the constellation has been optimized to maximize the service capability in the middle latitudes. This is partly because the metric of average capacity density implicitly assumes that the service capability is averaged over the ground surface whereas populated ground areas, shown in Figure 3, occupy a small proportion of the Earth's total area, resulting in a large percentage of the capability being wasted on oceans and unpopulated ground.

Another concern is the limited link budget. The single-user throughput provided by a single satellite is very limited, leading to less utilization of the spectrum assigned to satellite communications when compared with the terrestrial scenario.

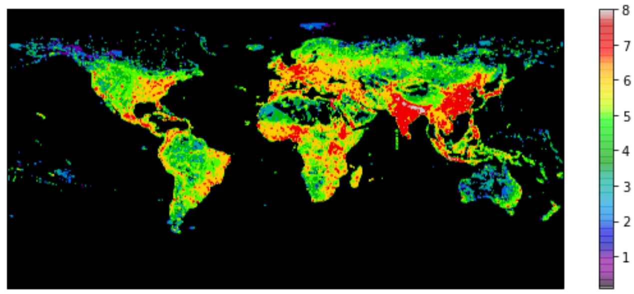


Figure 3 Global population density (generated from [13])

To fully unleash the service capabilities and address these fundamental challenges, two potential solutions are provided.

- On-demand coverage for imbalanced requirements

The beam-hopping concept is introduced to adapt the imbalanced requirements over the satellite coverage area [14–15]. Satellites can scan through a set of predefined beam hopping patterns, during which beams are active for a period of time for different areas to fulfill the service requests.

Beam-hopping technology can use all the available satellite resources to provide services to specific locations or users. By adjusting the beams' illumination duration and period, different offered capacity values can be achieved, i.e., the imbalanced requirements in different beams can be satisfied.

Additionally, beam hopping can reduce co–channel interference by placing inactive beams as barriers between co–channel beams [15]. However, beam hopping brings new challenges to LEO/VLEO satellite communications, e.g., designing beam-hopping illumination patterns to completely satisfy location-based service requirements, and considering restrictions of on-board capabilities.

Figure 4 demonstrates a snapshot of beam-hopping scheduling during a period of satellite movement. The target area where UEs are located is covered by 4 satellites (cells) at the time of observation, whose coverage topologies are shown in red, green, blue, and black, respectively. Each satellite uses at most eight beams (i.e., the highlighted beams out of all the candidate beam locations in the figure) to provide services to the connected UEs. In the LEO/VLEO system, due to the high mobility of satellites and the fact that traffic demand and buffer status of UEs will vary over time, both the candidate beams and the highlighted (illuminated) beams will be different between snapshots.

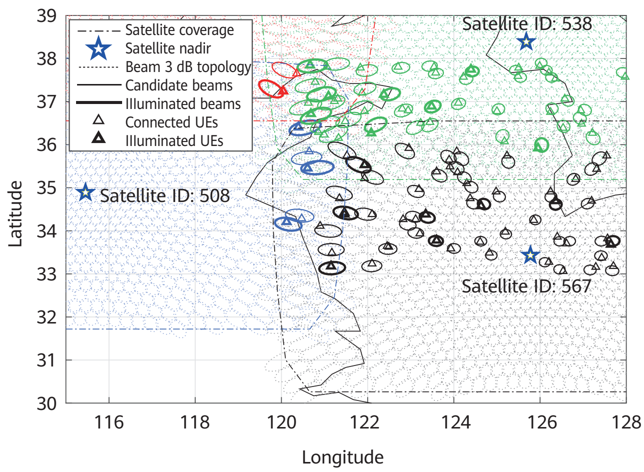


Figure 4 A snapshot of beam-hopping scheduling

Figure 5 illustrates the average throughput for different scheduling algorithms based on the simulation of a time period. As can be observed, the throughput of the beam-hopping based algorithm better matches the UEs' required capacity than the baseline Round Robin-scheduling, especially for UEs with higher traffic demands.

Multi-satellite cooperative transmission is another enabler to achieve on-demand coverage. This technology enables one user to receive multi-satellite signals simultaneously. Future LEO/VLEO mega constellations will include tens of thousands of satellites, which is the basis of multi-satellite cooperative transmission.

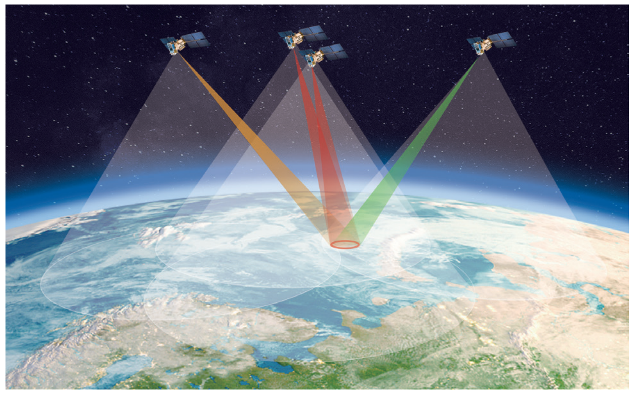


Figure 6 Multi-satellite cooperative transmission

Accordingly, the transmission rate can be increased when a user receives signals from multiple satellites at the same time, or when multiple satellites receive signals from the user, as shown in Figure 6. Based on cooperative transmission, the peak capacity density can be significantly increased as shown in Table 1. Such a scheme makes sense considering the fact that only a very small percentage of the covered area is in service and multiple satellites are usually visible with a mega constellation. The multi-satellite cooperative transmission technique can also resolve the insufficient link budget problem that arises due to the limited transmit power of one user or satellite.

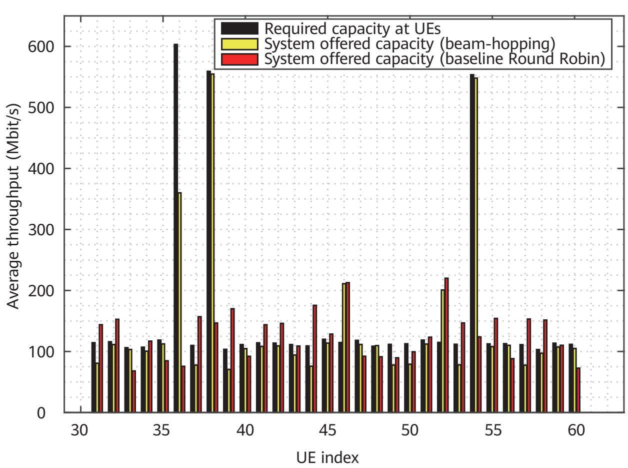


Figure 5 Throughput with and without beam hopping

Table 1 Performance of multi-satellite cooperative transmission

Satellite Coverage Area (km^2)	About 2,000,000
Beam Coverage Area (km^2)	About 1,000
Average Capacity Density (Mbit/s/km^2)	About 3.6
Cumulated Capacity Density (Mbit/s/km^2)	About 7,200

- Multi-beam precoding for high spectral efficiency.

The spectral efficiency of existing satellite communications is much lower than that of terrestrial networks due to the insufficient link budget and co-channel interference among beams. Multi-color frequency reuse is usually adopted to mitigate the co-channel interference in satellite communications, which leads to very low system spectrum efficiency. Precoding technique, which is widely used in terrestrial communications, can be employed to mitigate the co-channel interference [16]. As shown in Figure 7, multi-beam precoding can provide full-frequency reuse and improve the spectrum efficiency in VLEO/LEO satellite communications scenarios.

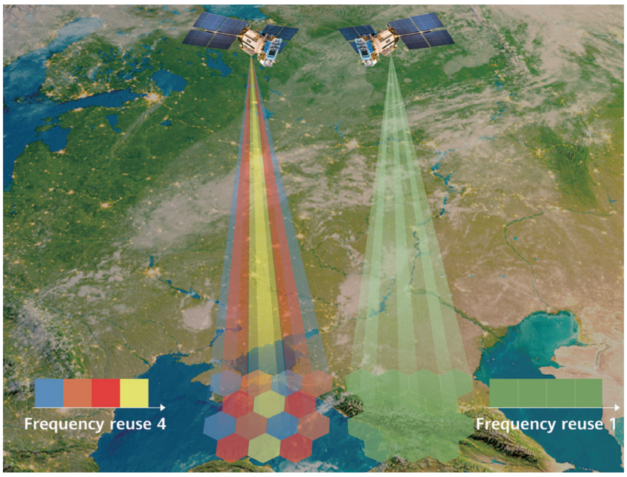


Figure 7 Multi-beam precoding

Multi-beam precoding for satellites based on full channel feedback is not preferred as there will be a large feedback delay due to the long transmission delay. As the main characteristic of the satellite channel is Line of Sight, the multi-beam precoding matrix can be calculated based on the large-scale channel which is approximately decided by the relative location between the UE and the satellite. The performance of location-based multi-beam precoding is shown in Figure 8. It can be observed that, compared with no precoding (blue bar), the introduction of multi-beam precoding (green bar) can result in a huge gain in terms of total throughput during the time the satellite provides services.

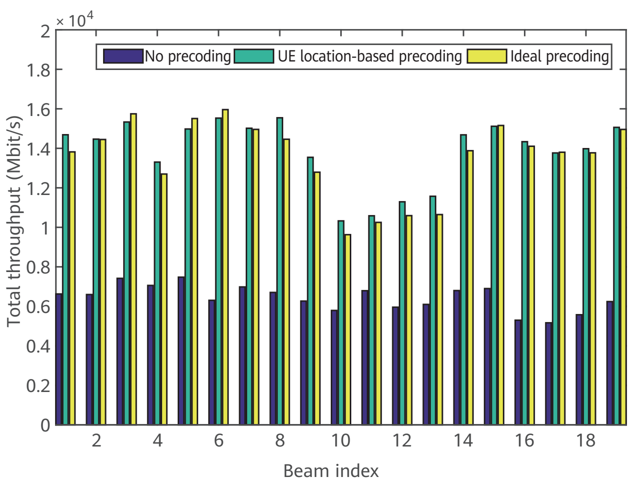
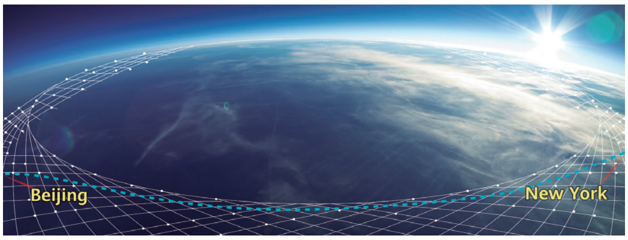


Figure 8 Throughput with and without multi-beam precoding

4.3 Dynamic Topology and Routing Algorithm

The end-to-end delay based on the VLEO constellation is expected to be lower than that based on the terrestrial Internet. Figure 9 shows the ISL-based route between Beijing and New York with the shortest distance as well as the ping Round-Trip-Time (RTT) comparison between ISL-based route and typical Internet-based route. The ping RTT of the typical Internet-based route is about 250 ms while that of the ISL-based route can be as low as 100 ms along the satellite-based route.



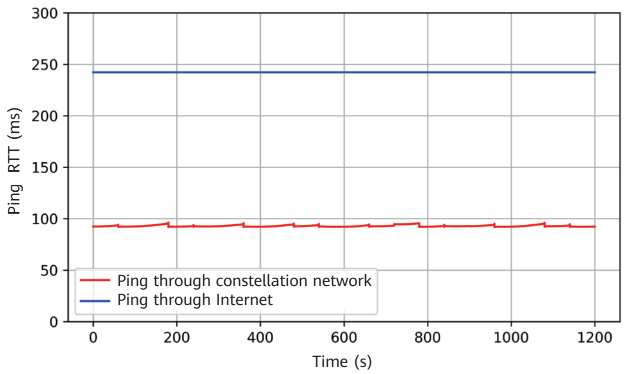


Figure 9 ISL-based route (upper) and ping RTT comparison between ISL-based and terrestrial-based route (bottom)

The potential size of mega constellations is a concern when considering routing and forwarding. Specifically, routing table sizes can grow dramatically as the satellite network grows in size. In terrestrial networks, large networks are generally partitioned into smaller networks, either by creating subnets, or by utilizing some functionality, for example Open Shortest Path First (OSPF) areas or Intermediate System to Intermediate System (IS-IS) link levels. In a satellite network, the network is in continual motion and therefore will require continual network segmentation. Highly dynamic subnetting will have detrimental consequences for the data plane.

However, each network node in a satellite network follows a predefined orbit around the Earth. Predictive routing is a specific class of routing and forwarding mechanism that takes advantage of the predictable nature of network topology changes. Unlike traditional routing and forwarding, where network nodes use flooding to signal topology changes, predictive routing allows the nodes to periodically switch routing tables that reflect the network topology graphs at different points of time. Each node contains an almanac that includes information such as the topology and time validity period. Provided that all nodes coordinate and have an accurate notion of time, the resulting network topology will appear stable. The periodicity of these changes will depend on factors such as the LEO/VLEO altitude and can be calculated by the satellite, or by a ground-based network control center.

Although the predictive routing mechanism works well in small networks as long as there are no unexpected events, an unpredicted link failure may result in a routing failure, the duration of which depends on the almanac update period. Typically, almanac updates are usually scheduled at a much slower rate than those of the traditional link state protocols, leaving nodes with outdated topology for a longer period of time. Furthermore, it requires precise timing synchronization among the satellite nodes to get all nodes updated, resulting in the data plane becoming unreliable during this time period.

Orthodromic Routing (OR) is a promising solution to address the above problems by trading some packet losses (especially when there are sufficiently large holes in the ISL mesh) against massive scalability. Since a sub-arc of the great circle between two points A and B is referred to as the Orthodrome, OR is defined as the shortest path routing on the surface of a unit sphere. Figure 10 shows the Orthodrome.

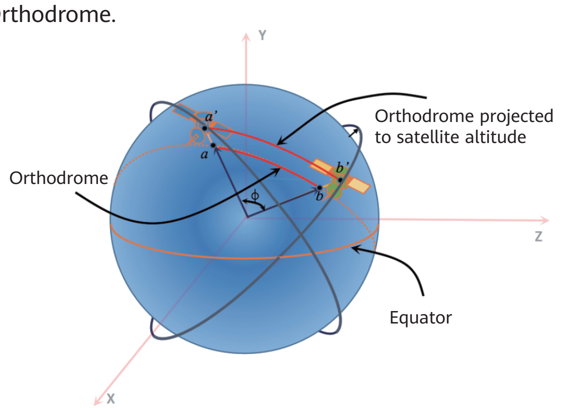


Figure 10 Orthodrome relative to the great circle

OR consists of an addressing and forwarding plane, a path computation algorithm, and a limited flooding algorithm. The addressing plane of OR embeds the <X,Y,Z> coordinates of a point on the unit sphere for both the source and destination into the IP header thus obviating the need for constant translation of identification and location. The data plane then forwards packets to the closest satellite within a relatively small flooding vicinity along the shortest path (following the ISLs) to that satellite. All satellites also have coordinate-based addresses which are a strict function of time. Therefore, all satellites can calculate their own addresses and the addresses of the satellites in their flooding region as a function of time. Flooding over a limited radius of hops and then performing path computations on those limited radius graphs is well known and Dijkstra produces the first hop needed by the forwarding plane.

Based on the above concepts a class of OR algorithms are defined as OR(r) where r is the radius in hops of the floods. OR(∞) functions as link state protocols while OR(1) performs simple geographic routing (forwarding data to the closest neighbor). Of interest is to determine which OR(r) is to be used for a given constellation size and expected link failure probability. We have conducted simulation tests on some of these algorithms and the simulations show that OR(r) can produce robust distributed routing for a relatively small r value and 10-20% link failure probabilities. This means that OR(r) can be tailored to a given constellation size and worst case failure probabilities to provide fully distributed forwarding at low loss rates.

Additionally since OR(r) may require a forwarding table with $O(r^2)$ entries, we explore several hardware solutions to pick the appropriate entry with maximum parallelization and thus appropriate for minimum clock cycle hardware forwarding at line rates.

The OR(r) algorithm as described above is executed at each hop. Therefore, the choice of gateway/intermediate nodes can change at every step towards the destination. We also have a slight variation on OR(r), where once a gateway/intermediate node is chosen, the packet is encapsulated with a source route such that the gateway can be used prior to extending its path further towards the destination. We refer to this as Piece-Wise Shortest Path OR(r) algorithm OR(r)-PWSPF.

Simulations are set up to compare the OR(r)-PWSPF with the basic OR(r) algorithm against a theoretical but non-existent full knowledge Dijkstra algorithm. The Dijkstra algorithm based on full knowledge represents an upper bound on what is possible for a given constellation. Figure 11 shows the CDF for path lengths (costs) for the different algorithms, with full knowledge Dijkstra in blue, OR(20) in red and OR(20)-PWSPF in yellow. A comparison of failed routing pairs i.e. source-destination pairs that cannot be reached under 30% link failure probabilities shows that both OR(20) and OR(20)-PWSPF come within 0.25% of full knowledge Dijkstra.

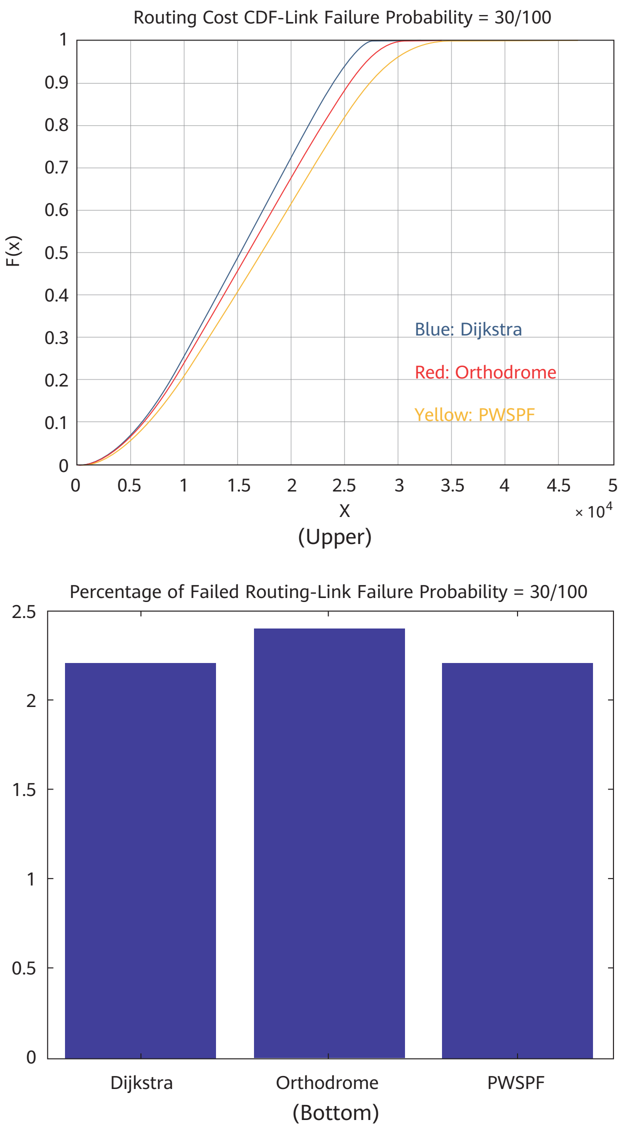


Figure 11 OR(20) routing cost comparisons and failed routing pairs for 30% link failure probabilities

It can be concluded that both OR and OR-PWSPF are capable of delivering performance that is very close to performance in an ideal scenario, but require much less control (flooding) traffic and are thus more favorable to use in a highly dynamic network.

The orthodromic family of routing algorithms employs precise local topology views at each node for global routing. Nodes in these methods only react to network events that happen in their own region, and they are unaware of events that happen elsewhere in the network. These techniques as discussed earlier, provide good performance in comparison with the traditional link state protocols. But the lack of convergence with respect to the global topology in these approaches might result in prolonged sub-optimal paths during network failures.

To solve the above mentioned issue, the routing can be via multiple-precision regions. Each node's link state database and topology graph consists of multiple zones/levels/regions/radii. Each zone has a degree of precision with respect to the network event refresh time. The following illustrates an example of a multiple-precision region network graph in a node.

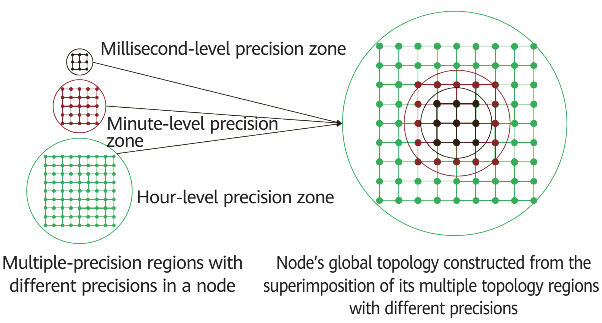


Figure 12 Multi-precision region graph: regions

Different techniques and strategies can be employed to deliver updates to a node for each of its topology zones based on the zone's precision requirement. While one zone can use an almanac, for example, the other can use traditional or limited flooding.

The nodes use the shortest path to the destination based on their global view of the network which now consists of multiple precision levels. This method can be applied to networks that employ traditional routing or networks that employ OR or OR-PWSPF algorithms to deal with node mobility in satellite networks and employ geographical addressing.

This technique shares the advantages provided by OR algorithms and allows the use of large flat topologies in network operations.

Finally, in order to limit the dynamic change of the satellite constellation topology, ISLs are usually assumed within the same constellation layer, and each satellite can have only two intra-plane and two inter-plane ISLs. This greatly compromises the communication capability of the entire network, and the optimal bandwidth and minimum delay cannot be achieved. Therefore, new routing algorithms are expected to accommodate constellations with more free connections among satellites e.g. across layer connections, thus extending the capability boundaries of the LEO/VLEO constellation.

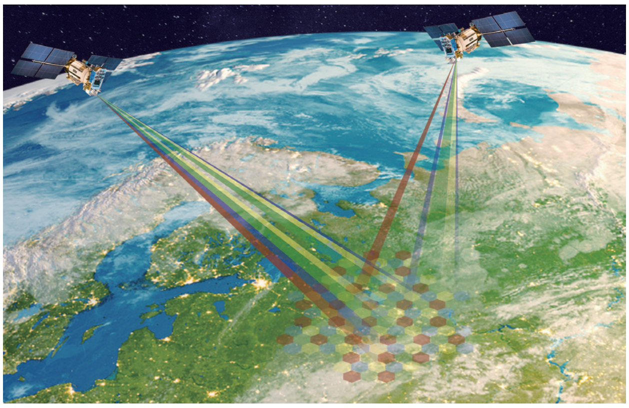


Figure 13 Massive-beam satellites

4.4 Powerful On-board Capabilities

The on-board capabilities call for thorough enhancements to accommodate communication requirements of NTN for 6G, mainly in on-board processors, radio frequency subsystem, antennas, and data transmission algorithms. Massive-beam satellites with on-board data processing capabilities and advanced algorithms will play a key role in future low-orbit satellite communications, providing more linking capabilities for users over the coverage area through frequency and beam traffic reconfiguration.

In future NTN, massive-beam high-gain phased array antennas will be equipped to prevent the extremely high path loss from space to ground. Assuming the altitude of the satellite is 300 km, the free space path loss is around 170 dB at Ka band with an extra loss of 6 dB due to rain. When the diameter of the satellite payload antenna is 1.0 m, the maximum antenna gain can be assumed as 45 dBi and the equivalent isotropically radiated power (EIRP) may reach 50 dBW, which is subject to the power restrictions on satellites. The typical diameter of a ground UE antenna for the Ka band is 0.5 m, which leads to a maximum gain of 34 dBi and a G/T value of 8.5 dB. Approximate calculation shows that the downlink signal-to-noise ratio (SNR) may reach up to 27 dB with a bandwidth of 400 MHz. The signal quality is sufficient to support higher-order modulation of 64QAM. The data rate achieved by a single beam is 1200 Mbit/s and the spectrum efficiency is 4.8 bit/s/Hz, considering interference.

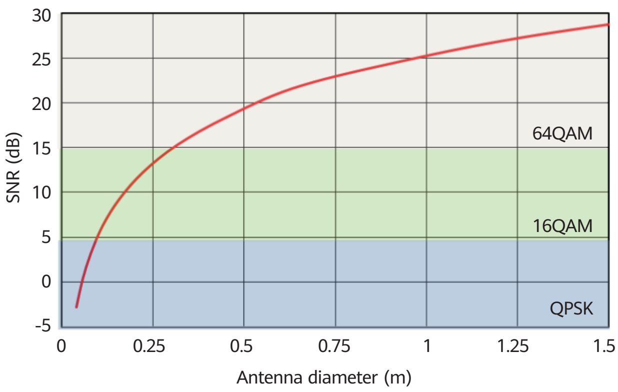


Figure 14 Available SNR for different satellite antenna diameters

The challenge is to find a way to generate these beams by utilizing the limited physical space on the satellite. The digital beam forming (DBF) method is considered a promising solution for future phased antenna arrays, in which multiple beams are generated in the digital domain. The digitization of the Tx/Rx data can also provide maximum flexibility and dynamic range in large systems [17]. The practical challenges to implementing DBF are the large amounts of data that needs to be processed and the use of sophisticated transceivers that consume high amounts of power, which cannot be provided by satellites. The development of digital integrated circuits and mixed-signal integrated circuits makes the DBF implementation realistic. In [18], a full DBF transceiver is designed for millimeter wave (mmWave) application. A maximum of 20 digital beams are generated from 64 RF channels. In the future, the number of beams will extend to over 1000 and RF channels to over 4000. The progress in RF components and materials also helps reduce the power consumption and improve the on-board capabilities.

4.5 Low-Cost Manufacturing & Service

Reducing the satellite components' manufacturing cost and the service price is the prerequisite for making satellite communications a part of daily life.

Regarding the manufacturing, a full integration of satellite communications into the cellular system is expected to be the most effective way to reduce the cost of communications components in ground segment devices like UEs, gateways, as well as the on-board processing system. With a unified air interface design capable of satellite communications and terrestrial communications, the baseband chips and components of satellite communications can make full use of the economies of scale of the cellular industry, leading to much lower chip and device costs.

It is a challenge to reduce the cost of the space segment to achieve low-cost manufacturing. The space-class components are radiation-hardened and screened to make sure they are reliable enough in the space environment. Because this process is not industrialized, the cost is extremely high. In addition, because the quantity of radiation-hardened devices is very small, manufacturers have no incentive to perform radiation-hardening for the latest products, leading to a delay in the delivery of space products by several years or more when compared with their latest commercial counterparts. Low cost, high performance and low lead time are the requirements for commercial satellite parts. In recent years, there have been some explorations on using commercial-class devices i.e. the Commercial-Off-The-Shelf (COTS) parts in spacecrafts. Optimized processes, such as a better balance of the cost and reliability in the screening, new shield designs, and a fault detection and recovery mechanism, are needed to ensure the stability and commercial efficiency of spacecrafts.

The service cost will also benefit from the full integration between satellite communications and cellular communications since it is also related to the economies of scale. Currently, the ecosystems of different constellations are isolated from each other and the number of users of each constellation is insufficient to make full use of constellation capacity, resulting in the cost per bit in existing satellite communications being much higher than that of terrestrial networks. In 6G, the wireless standards should be unified around the world, and with a single device, people should be able to freely roam between TN and NTN and between different NTNs. In this way, the network capacity of a satellite system can be much better utilized to reduce the overall service cost.

4.6 Interference Reduction and Co-existence

It is critical to find a way to prevent the interference between TN and NTN in order to ensure communication service quality. Frequency sharing between cellular and satellite communications is a hot topic that has been discussed in both the academia and the industry. However, the current frequencies allocated to cellular and satellite communications are usually isolated from each other. In actual practice, a gap is introduced to ensure that the out-of-band leakage of the waveform signal due to non-linear devices can be sufficiently low. Owing to the fast development of cellular communication, the spectral efficiency of terrestrial networks has dramatically increased, and is much higher than that of satellite communications. The frequency resources allocated to cellular networks contribute more to human communication requirements. This motivates cellular operators to obtain more frequency resources from satellite operators to provide users with a better cellular experience.

Considering the fact that very limited frequency resources are available, it is more important than ever to design a frequency sharing mechanism that not only considers the comprehensive utilization of the spectrum, but also meets the needs of different types of communications scenarios from a technical and neutral perspective. In general there are several hierarchical frequency sharing technologies that can be considered to reduce the interference among the different types of satellite communications and cellular communications.

- Space isolation

The most straightforward method for interference reduction is space isolation. The same frequency resource can be allocated to both cellular and satellite networks that are geographically far away from each other to prevent any possible interference. For example, the frequency assigned for cellular operators in terrestrial networks can also be used for satellite communications on an ocean provided that the two deployment areas are geographically far away so that the maximum transmitted signals from the cellular base station would be much lower than the background thermal noise of the satellite communications terminal receiver after long propagation, and vice versa.

An application of space isolation in scenarios where the cellular and satellite networks are striving for sharing the frequency resource is shown in Figure 15. For a cellular base station, the space area around this base station will be noted as an "electronically fenced area" where satellite beams are not allowed.

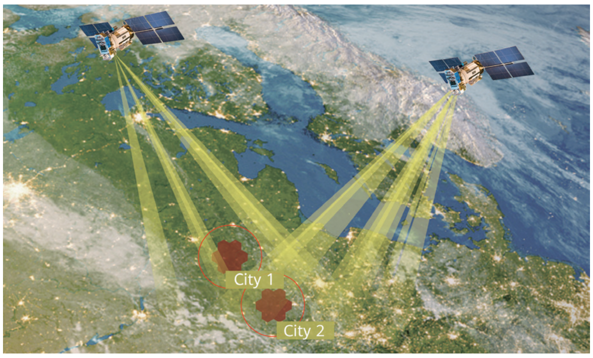


Figure 15 A demo of "electronically fenced area"

The size of the electronically fenced area will significantly affect the possible interference level from the LEO/VLEO satellites. Figure 16 shows one snapshot of the interference level in terms of interference noise ratio (INR). The satellite beams causing INR above -10 dB and -5 dB are marked in yellow and red, respectively, with difference in the size of the electronically fenced area. A 54 km-wide electronically fenced area is sufficient to eliminate all interference above -5 dB for the considered case.

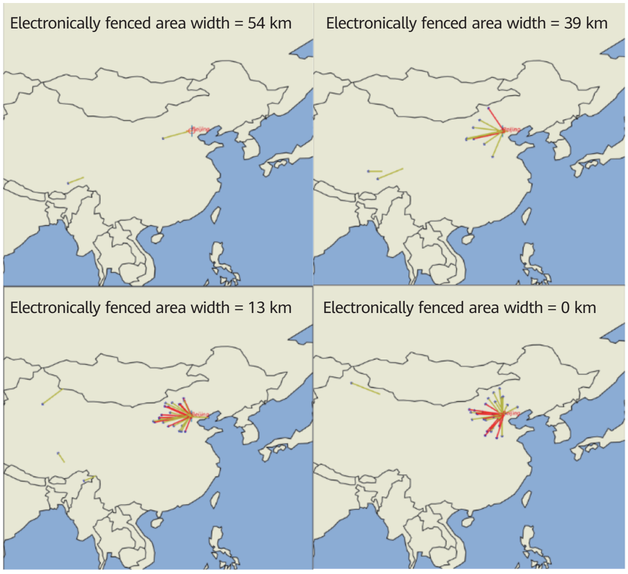


Figure 16 Application of space isolation in interference avoidance between satellites and cellular base stations

Figure 17 shows the interference along a time interval with two electronically fenced areas of width 0 km and 54 km. A larger isolation distance can effectively reduce the probability of receiving high INR.

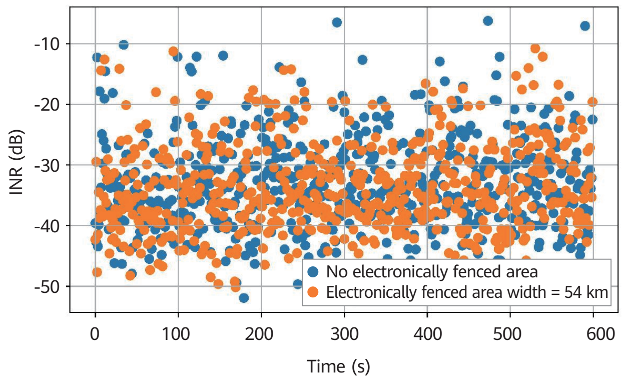


Figure 17 INR levels within a time interval of 600s with different electronically fenced area widths

- Angle isolation

For scenarios targeting mmWave bands where only UEs with directional antenna are deployed, angle isolation can be considered to prevent the interference caused from different systems. Considering a serving area illuminated by signals of the same frequency band from different systems, the arrival angle of the signals may be far different from each other. At the receiver side, the huge side-lobe reduction of directional UE provides good spatial filtering and can eliminate the interference. The potential interference to other systems can also be eliminated because the transmitted signals will experience huge attenuation due to the directional antenna.

- Scheduling-based interference coordination

Scheduling-based interference coordination has been deployed in cellular communications systems to alleviate the interference in cell edge areas. With close interaction among neighboring base stations, joint decisions can be made among those stations to send signals to UEs at the cell edge with staggered frequency resources in order to prevent interference. Compared with the traditional sensing-and-decision procedure, coordination-based scheduling attempts to solve the interference issue in a proactive way, and thus provide better user experience.

However, coordination-based scheduling is rarely used between the cellular and non-terrestrial networks for the time being since they are isolated from each other. By taking the advantage of integrating cellular and satellite communications, scheduling-based interference coordination is expected to become possible.

5 Conclusion

The successful realization of LEO/VLEO-based NTN communications calls for joint efforts from the academia and industrial communities. The ongoing development of new technologies and the growing interest and investments in space applications is extending the boundaries of potential LEO/VLEO-based communications to new heights. In addition to the technical aspects of satellite communications itself, a fundamental integration of cellular- and satellite-based communications at the physical layer from day one is also the key to the commercial success of LEO/VLEO-based satellite communications in 6G. The NR-based NTN discussion in 3GPP provides an excellent platform that traditional cellular and satellite communities can use to work together to build a fully integrated network. As the advanced frequency sharing schemes between the cellular network and NTN mature, regulatory authorities may have more room to assign frequency resources in an efficient way.

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