Satellite communication benchmarking with terrestrial 5G networks

White paper

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Due to advances in launch capabilities and increasing production volumes, satellite communications are addressing increasingly wider customer segments. Further cost reductions and access to new spectrum will only increase their relevance, especially to rural and remote users without access to 4G or 5G fixed wireless access (FWA) or fiber. Where FWA is available, however, it remains a more compelling offer than existing satellite broadband services. Satellite-based Direct-To-Device (D2D) services are starting to be commercially deployed across the globe, which support low data-rate services for consumers as well as emergency and public safety connectivity services. We argue that D2D can be considered as a solution for mobile operators to complement their terrestrial network coverage and will be an integral part of 6G mobile networks from day one. In this paper, we look closely at current and planned satellite services benchmarking them against 5G FWA services and make recommendations to service providers on how best to respond to this new class of sometimes-competing and sometimes-complementary communications services.

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Executive summary

The satellite industry is currently being disrupted by the rapid introduction of large low Earth orbit (LEO) satellite constellations, which enable lower latencies and higher throughputs than more traditional geostationary satellites. This evolution has been driven by a dramatic decrease in launch and production costs for LEO satellites over the past decade.

For terrestrial mobile operators, two satellite use cases are of particular interest (see Figure 1):

1. Satellite broadband connectivity to a fixed device, competing with terrestrial 5G fixed wireless access (FWA) and fixed networks
2. Mobile connectivity to a smartphone offers supplementary coverage to terrestrial mobile services.

Today, Starlink is able to provide a satellite broadband connection at a performance almost similar to that of 5G FWA and, in some regions, even exceeding the performance of fixed networks. It leverages high-frequency satellite spectrum (10 GHz and above) for connecting to proprietary user terminals containing phased arrays and can readily be made available across a whole country. This makes for an attractive solution in areas without access to fiber or 5G FWA. On the other hand, 5G FWA is capable of much higher capacity densities (Mbps per km^2) and at a significantly lower price in areas within terrestrial coverage. This makes 5G FWA better suited for serving urban and suburban areas, which have higher user densities. 5G FWA currently has roughly 10x more subscribers than Starlink globally, and we expect that market share difference to remain substantial wherever 5G FWA is available.

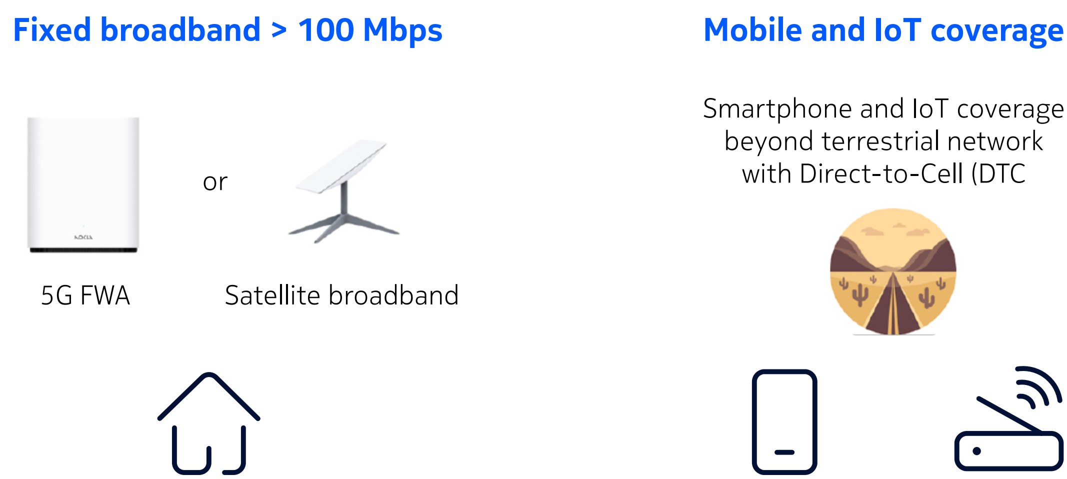
Satellites can also provide connectivity directly to smartphones or IoT devices using sub-3 GHz spectrum, known as Direct-to-Device (D2D) or Direct-to-Cell (DTC) service[1]. For example, AST SpaceMobile has recently demonstrated single-user data rates of ~20 Mbps to an unmodified smartphone leveraging a LEO satellite equipped with a phased array of ~64 m^2. Text-messaging D2D services are commercially available today and are expected to soon include support for voice and low-rate data communication as well. D2D is very suitable to provide low-rate data connectivity in areas without coverage from terrestrial networks, both for consumers and for emergency and public safety services. The first generation of D2D services can connect to legacy LTE and IoT devices, with an evolution path to 5G-based connectivity. Current D2D services either leverage mobile satellite spectrum (e.g., Apple/Globalstar) or reuse terrestrial mobile spectrum from MNOs (e.g., AT&T/AST, T-Mobile/Starlink). Recent commercial agreements (e.g., AST/Ligado) indicate more satellite spectrum-based solutions can be expected to emerge; including those per 3GPP Rel-17 (and later releases) that contain NTN-specific enhancements on both the device and the network side compared to terrestrial standards. D2D can be an additional tool in the mobile operators' toolbox to complement their mobile networks' coverage (e.g., to expand it to 100%) and is expected to be an integral part of 6G mobile networks from day one.

Nokia's recommendation is that mobile operators should take advantage of their assets to remain most competitive in this new era of satellite connectivity. Mobile operators should expand 5G FWA service and coverage to defend their market share from the evolving capabilities and market penetration of the increasing number of satellite broadband operators. Once a customer has a 5G FWA connection with a satisfactory performance and a lower price than that offered by a satellite operator, there is little motivation for switching. Mobile operators should also leverage D2D service providers to offer low data rate service to areas not covered by their terrestrial network and develop D2D partnerships based on an evaluation of their spectrum assets and network coverage characteristics. Finally, operators should also consider new opportunities enabled by satellite connectivity, both in terms of business opportunities, such

1 We will use D2D for connectivity to smartphones (covering both pre-3GPP Rel-17 and Rel-17+ over satellites in the rest of this paper).

as IoT, public safety and solutions for network resilience, as well as network deployment opportunities, including satellite backhauling for base stations.

Figure 1. (Left) Satellite broadband connectivity to a fixed device competes with terrestrial 5G fixed wireless access (FWA). However, 5G FWA offers a higher capacity density and has a lower price. (Right) Satellite mobile connectivity directly to handheld and IoT devices, on the other hand, is more complementary to terrestrial mobile networks. It can be leveraged by terrestrial operators to extend their coverage to ~100%, albeit at limited data rates.



Introduction

Over the last ten years, the rapidly decreasing cost of launching and producing satellites led to a drastic increase in the number of satellites in LEO orbits. The number of satellites launched per year has dramatically increased from less than 300 per year in 2015 to 3,000 per year in 2024. The number of commercial satellites (in all orbits) is expected to nearly quadruple over the next four years, from 8,000 in 2024 to more than 30,000 in 2029 [1]. US-based Starlink currently operates the largest satellite constellation with ~7,000 active satellites and is expected to maintain its space-presence dominance for the near future. Second in size is European-headquartered Eutelsat-OneWeb with ~650 satellites. However, US-based Amazon Kuiper is expected to soon become the second largest Western operator with more than 3,000 satellites. European-based IRIS (Infrastructure for Resilience, Interconnectivity and Security by Satellite) is expected to be available for government services starting in 2030 with 264 LEO satellites. Chinese mega-constellations are projected to start growing fast very soon, having announced several constellation deployment plans involving thousands of satellites, for example, Guowang and Qianfan.

Historically, satellite communication was mostly provided by geostationary-Earth-orbit (GEO) satellites at an altitude of ~36,000 km, allowing them to serve large areas with very few satellites (see Figure 2). However, most of the current satellite deployments focus on low Earth orbit (LEO). LEO satellites operate at a much lower altitude of 200-2,000 km, which enables them to provide higher throughputs and lower latencies compared to geostationary satellites. On the other hand, a LEO constellation requires many more satellites to achieve global coverage.

Terrestrial networks are predominantly used to provide coverage in populated/inhabited areas. As a result, vast areas such as very deep rural areas, oceans, deserts and polar regions, lack internet connectivity. This new generation of LEO communication satellites can provide connectivity to any location on Earth and can reach performance similar to terrestrial 5G FWA. Satellites can even be used to provide connectivity directly to smartphones (D2D) to complement terrestrial network coverage.

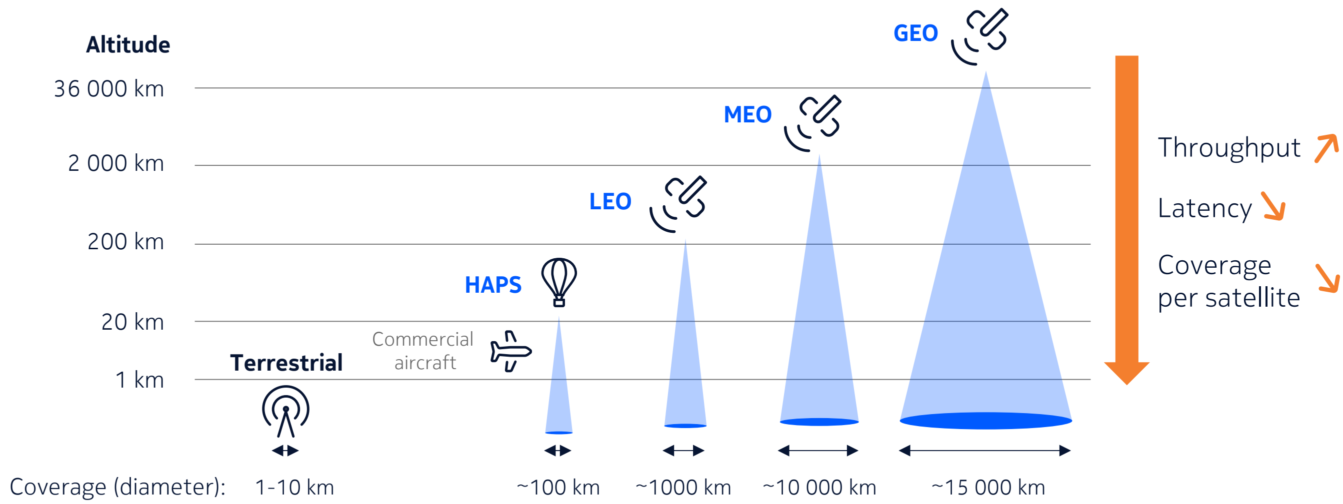
This paper illustrates the capabilities, benefits and limitations of these new satellite constellations by comparing them to terrestrial 5G networks. We will analyze two use cases in this paper:

1. Broadband connectivity to a fixed device[2]
2. Mobile connectivity to a smartphone.

The broadband connectivity benchmarking compares Starlink's fixed satellite services (FSS) with 5G FWA. The mobile connectivity benchmarking compares satellite D2D (AST SpaceMobile and Starlink) with terrestrial 5G mobile networks.

2 Note that some satellite solutions also support mobility scenarios for such devices (providing support for mounting them on a moving vehicle or boat). We also classify these under the "broadband connectivity" use case.

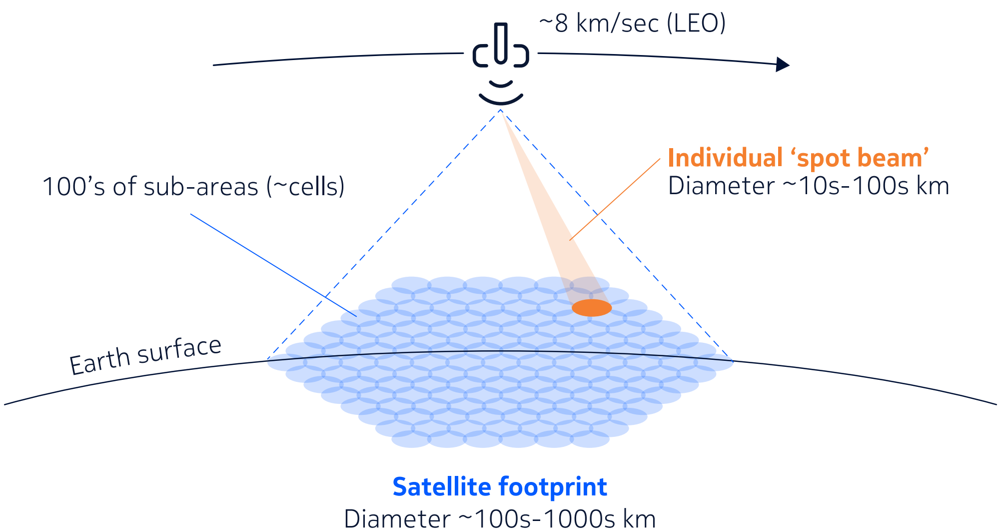
Figure 2. Different satellite orbits have different advantages. The higher orbits require fewer satellites to achieve global coverage, while the lower orbits allow for a better performance in terms of throughput and latency. The current satellite constellation boom mostly focuses on LEO orbits.



Satellite networks

Unlike GEO satellites, whose orbital speed matches the rotation of the Earth, making them occupy a seemingly fixed location in the sky, LEO satellites orbit the Earth in roughly 90 to 120 minutes. Seen from the Earth's surface, a LEO satellite moves from horizon to horizon in only a few minutes, orbiting the Earth at a dazzling speed of ~8 km per second. Modern satellites divide their footprint into many sub-areas, or cells, which they serve with individual spot beams. A single satellite orbiting at 500 km can cover 2 million square kilometers (i.e., its footprint). The area can accommodate approximately 1,000 cells, each with a diameter of 50 km, that the satellite is capable of serving. But the number of simultaneously active beams per satellite is typically lower than the total number of cells available in its footprint. The cells on Earth typically have a fixed location, with beams being continuously steered to compensate for the movement of the satellite. LEO satellites provide coverage for only a few minutes to any particular location on Earth. Therefore, when the satellite is no longer able to serve a cell, its service is switched over to the next satellite.

Figure 3. Modern satellites divide their footprint into many sub-areas, which they serve with individual "spot beams." The number of simultaneously active beams per satellite is typically lower than the total number of cells available in its footprint.



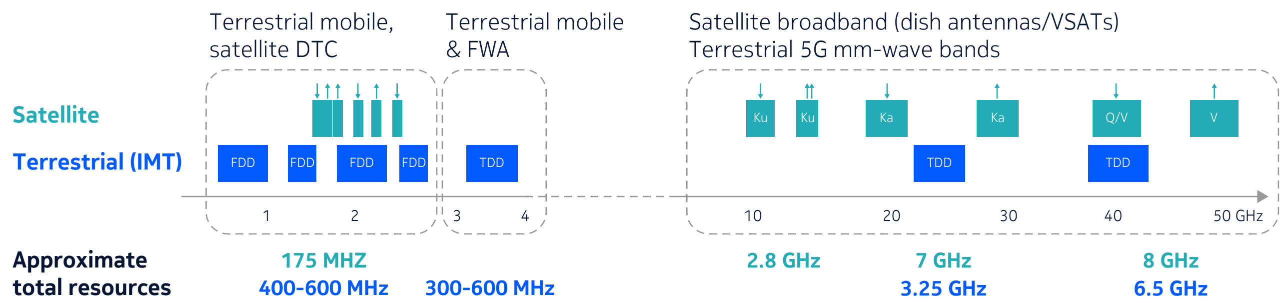
Spectrum bands for terrestrial and satellite communication

An overview of the spectrum usage for terrestrial and satellite connectivity is shown in Figure 4. 5G service—both mobile and FWA—is provided by mobile operators using licensed frequency-division duplex (FDD) and time-division duplex (TDD) spectrum at sub-6 GHz frequencies. 5G FWA also sometimes leverages higher-frequency mm-waves.

Satellite D2D currently uses the FDD[3] spectrum below 3 GHz, reusing the terrestrial spectrum bands. Fixed satellite broadband solutions mostly use frequencies above 10 GHz, like the Ku band (12–18 GHz) and Ka band (26–40 GHz). They are used by satellite broadband providers like Starlink, OneWeb, and Amazon Kuiper. Starlink also plans to use the V-band spectrum (40–75 GHz) to connect to fixed terminals in the near future. Fixed satellite terminals in the Ku/Ka and V-bands typically use directive antennas with high gains, which helps to compensate channel losses.

3 Satellite D2D and 3GPP NTN use FDD as a duplexing method, except for one TDD band, which is being specified in Rel-19 for NB-IoT.

Figure 4. Terrestrial and satellite networks typically use different spectrum bands, although some satellite direct-to-cell services also reuse terrestrial mobile spectrum. Lower frequencies are mostly used for communications with handheld devices, while higher frequencies are mostly used for communicating with around five fixed terminals. Upward/downward arrows above the satellite spectrum indicate Earth-to-satellite or satellite-to-Earth directions.



Terrestrial spectrum reuse for D2D

Terrestrial mobile spectrum is a precious resource for terrestrial mobile operators. One approach could be for the MNO to share part of their spectrum resources on a geographical basis. This means that the MNO would still utilize its entire spectrum resources where needed, allowing the satellite operator to utilize part of the (agreed) MNO spectrum for coverage in specific geographical areas distant from terrestrial infrastructure (e.g., deep rural and remote locations). The benefit of this approach is that the MNO would still be able to utilize all its spectrum resources. However, a disadvantage is that due to the much larger satellite cell sizes, provisioning D2D services in areas near existing MNO coverage could be challenging.

Another approach could be to exclusively allocate part of the MNO spectrum resources for D2D across the entire country. The benefit of this approach is that the D2D operator can more easily coexist with the partner MNO network and provision D2D services (partly) overlapping with terrestrial coverage, for example, to cover smaller dead spots. The disadvantage is that the MNO would not be able to leverage that portion of their spectrum holdings to provide terrestrial coverage with higher spectrum efficiency.

Using MSS satellite spectrum for D2D

It's also possible to use dedicated (MSS) satellite spectrum for connecting satellites to smartphones and IoT devices. This is, for example the case in the Apple/Globalstar partnership, which uses Globalstar's S and L-band satellite spectrum to directly connect Globalstar's satellites to Apple's iPhones for providing a messaging service when out of coverage of terrestrial mobile networks on iPhone 14 and later models. While in the Apple/Globalstar partnership, D2D communication is provided through bespoke communication protocols, 3GPP Rel-17 (and onwards) also specifies NTN on satellite spectrum bands for D2D services (e.g., in L and S band), introducing NTN-specific enhancements on both the device and the network side. An example of a partnership between terrestrial and satellite operators leveraging satellite spectrum is the Verizon/Skylo partnership, which leverages MSS spectrum for a satellite messaging service to select Android phones.

For the satellite operator, a potential benefit of using MSS spectrum is that it does not require terrestrial-spectrum partnerships with terrestrial operators across the world. Another benefit of using satellite spectrum is that it avoids cross-border interference issues, which are particularly challenging in smaller countries, for example, parts of Europe, due to the larger NTN cell sizes. The drawback is that existing 3GPP devices do not natively support these satellite bands. Hence, use of these satellite-specific bands can only be done by devices with compatible band support. We'll go deeper into these issues in future evolution in the "Future technology evolution" section at the end of the paper.

Licensing of terrestrial and satellite spectrum

Licenses for terrestrial mobile spectrum bands are auctioned by government agencies, often for billions of dollars. In exchange, the obtained license guarantees exclusive usage of that spectrum band.

In contrast, satellite spectrum licenses are administratively allocated and not sold exclusively to the highest bidder. Usage of those satellite spectrum bands is shared and allocated based on the condition that the new satellite service cannot impact the operation of existing satellite systems in the same spectrum. In FSS, interference impact is quantified before a license is granted and typically leverages mechanisms like antenna directivity (providing angular separation) and proper coordination with existing constellations. Mobile satellite services (MSS), connecting to omnidirectional portable devices that don't support antenna directivity, require operators to engage in multilateral spectrum coordination that effectively boils down to band-splitting.

The fact that satellite spectrum is not auctioned provides a cost benefit compared to terrestrial networks, which gave rise to some debate in the industry.[4]

3GPP and satellite networks

Historically, MSS and FSS services leveraged proprietary radio access technology and satellite spectrum. Besides applying this same model to smartphones (as in the Apple/Globalstar partnership), the new D2D satellite service model also enables smartphones to connect to satellites using 3GPP's LTE or 5G radio access technology. But there is more than one way to do that.

The first approach is the one used by current D2D services like AST SpaceMobile and Starlink. They work with existing phones,[5] without requiring any specific support for NTN functionality. Modifications on the network side fully address the satellite-specific challenges, including the significant and time-varying Doppler frequency shifts caused by the high speed of the satellites, as well as the large network and propagation delays. As far as the phones are concerned, the satellite is just another terrestrial base station. Spectrum-wise, this approach requires D2D operation in the terrestrial MNO frequency bands that are already supported by those phones in the MNO network. Such deployments must be done through business agreements of satellite operators with terrestrial mobile network operators who are the license holders of those bands.

The second approach is to operate according to the 3GPP Non-Terrestrial-Network (NTN) specifications, which started with 3GPP Rel-17 (see Table 1). These specify the use of digital pre-compensation by the phone to address the time and frequency shift due to satellite movement[6] and solutions to cope with large network delays. The main distinction is that supporting the NTN features outlined in 3GPP Rel-17 requires new phone models that support Rel-17 NTN functionality. Rel-17 specified 5G-based NTN mobile broadband and 4G-based NTN IoT communication.[7]

4 For example, in India Starlink and terrestrial mobile operators Reliance Jio and Bharti have openly clashed about satellite spectrum licensing. The matter eventually settled in favour of continuing the common practice of administrative allocation for satellite spectrum [2].

5 "Existing phones" refer to phones with no support for Rel-17 NTN.

6 This is based on the satellite network broadcasting information about the satellite's location, speed and direction of travel for the satellite (i.e., the satellite's ephemeris), which the phone combines with its own GNSS position to apply the required signal compensation.

7 NB-IoT and eMTC/LTE-M.

3GPP distinguishes two satellite payload architectures:

1. Transparent payload, in which the satellite serves as a repeater for the base station located on the ground, which offers the benefit of lowering the complexity of satellite on-board processing
2. Regenerative payload, in which all base station functionality is on board the satellite acting as a 4G eNodeB or 5G gNodeB and has the benefit of reduced control-plane delays, increased feeder link[8] efficiency, and support for inter-satellite links.

3GPP Rel-17 only specified the transparent payload architecture. Although regenerative architecture was officially introduced in Rel-19, in principle it's also possible to support it with Rel-17 and Rel-18. Rel-18 added features to improve coverage, enhanced mobility between NTN and terrestrial networks, and support for Ka band spectrum (26–40 GHz) to enable 3GPP-based fixed satellite services to dish-type UEs, also referred to as a very small aperture terminals (VSATs). Rel-19 will extend spectrum support to Ku-band spectrum (12–18 GHz), introducing RedCap[9] for NTN and multicast/broadcast with geofencing support. IRIS[2] is expected to be the first satellite constellation using 3GPP technology in Ku bands.

Table 1. NTN feature evolution in subsequent 3GPP releases, of which Rel-17 is the first. Most current D2D deployments are pre-Rel-17, which are compatible with existing 3GPP phones but are not based on 3GPP NTN standard releases.

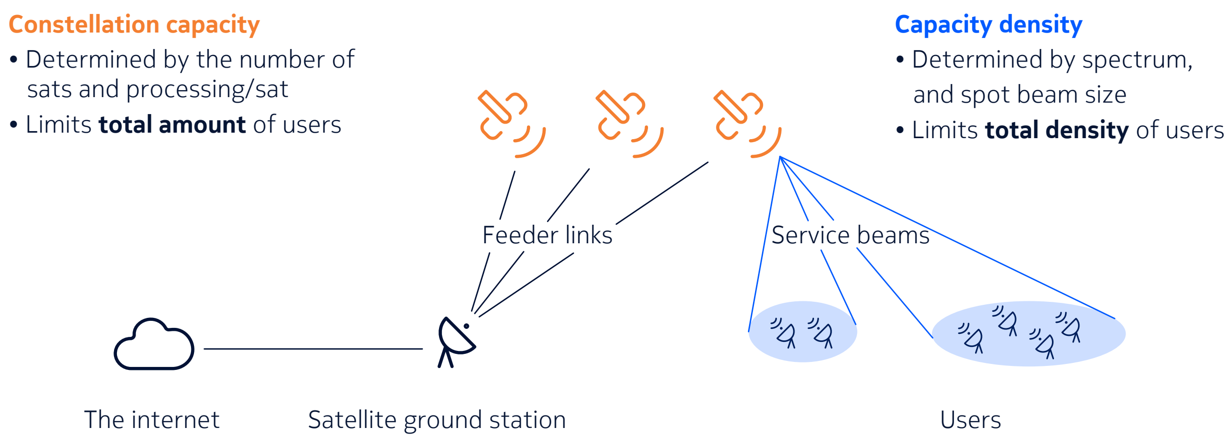
	Pre-Release 17	Release 17	Release 18	Release 19
Functionality	• Supports existing devices - NTN compensation fully on network side - Satellite = "just another terrestrial antenna"	• Requires Rel-17 device - NTN compensation in UE - Requires GNSS in UE • 1st 3GPP NTN release - Both broadcast and IoT • Transparent architecture	• Enhanced coverage • Improved NTN-terrestrial mobility	• RedCap for NTN • Multicast/broadcast • Regenerative architecture
Spectrum	Requires terrestrial spectrum partnership	S-band and L-band spectrum (sub 2 GHz)	K1 band (26-40 GHz) for 3GPP fixed satellite services	Ku band (12-18 GHz) for 3GPP fixed satellite services

Satellite network capacity

When considering a satellite network's capacity, one should make a distinction between the total constellation capacity and the local capacity density it can support. As illustrated in Figure 5, a constellation's total capacity is determined by the number of satellites in that constellation and the processing capability per satellite. This puts an upper limit to the total number of users that can be supported at a global level, regionally, and at a country level, based on the number of satellites that are used to provide coverage. Taking Starlink as an example, the cumulative global constellation capacity launched so far amounts to ~340 terabits per second (Tbps) [3].

8 The feeder link is the link between the satellite and the satellite ground station on Earth. The link between the satellite and the end user is called the service link.
9 Short for "reduced capability", RedCap targets 5G devices with lower performance requirements.

Figure 5. Satellite capacity limits include the constellation size, which determines the total number of users that can be supported, and the spectrum and beam sizes, which determine the local capacity/user density.



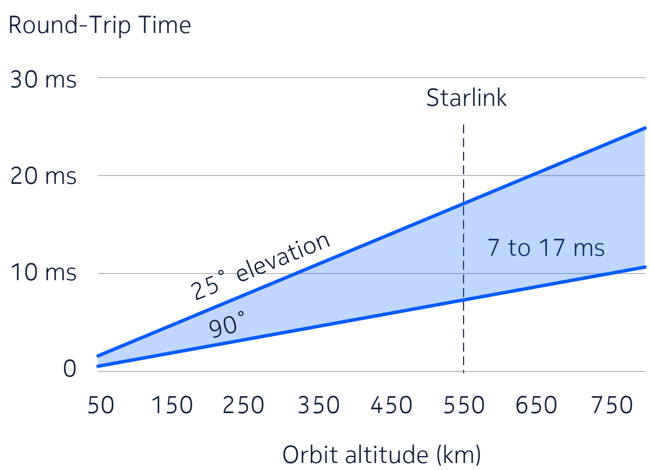
On a more local level, the capacity density (i.e., Mbps/km^2) determines the number of users that can be supported within a smaller geographical area. The limit is determined by the usable spectrum per spot beam, as well as the area covered by a single beam (within which all users share the beam's capacity). The beam area on the Earth's surface is mainly determined by the frequency used, the size of the phased array (larger phased arrays increase the ability to generate narrower beams), and the orbit altitude. There is some capability for beam shaping in the satellite phased arrays, but it is very limited compared to cell size scaling in terrestrial networks.

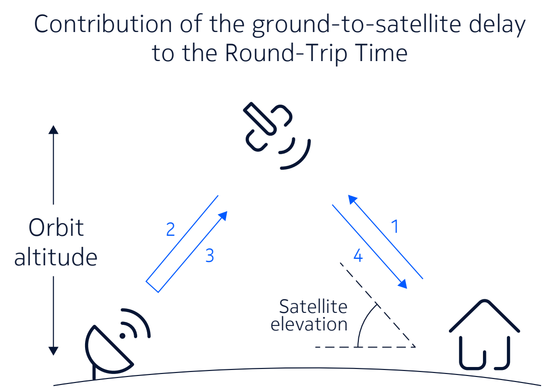
In terrestrial mobile networks, cell sizes are adapted to the population density. They are much smaller in urban areas compared to rural areas. This increases the local capacity density to address the increased user density in the area. In satellite networks, cell sizes are largely invariant and much larger than terrestrial cell sizes in terrestrial mobile networks. Taking Starlink as an example, a single user beam (i.e., a single cell) from their first generation of satellites has a diameter of ~22 km, covering an area of ~380 km^2. All users within this area need to share the spectrum and the capacity of that beam. Although Starlink can achieve single-user data rates exceeding 100 Mbps leveraging Ku and Ka band spectrum, new user activations are limited in certain regions where the service is operating at maximum capacity density [4].

Satellite network latency

End-to-end latency is determined by three major contributors: the propagation delay, the interface delay (limited by PHY and MAC layer protocol structures and related processing times) and queuing delay (dependent on the network congestion and buffer sizes).

Figure 6. If the application server is located on Earth, the round-trip time will be (at least) four times the propagation delay from the Earth to the satellite. Depending on the elevation angles between the user, the satellite, and the ground station, the minimum round-trip time will vary between the two blue lines (of the left figure).





For satellites, the propagation delay is both terrestrial (distance between ground station and data center) and non-terrestrial (distance between the satellite and the user or ground station). The interface delays also include satellite beam-scheduling delays, while queuing delays can occur both on satellite and ground equipment. The non-terrestrial propagation delay is determined by the satellite orbit altitude: at an altitude of 550 km, one-way propagation from ground to satellite takes about 1.8 milliseconds (ms) if the satellite is at 90 degrees elevation (i.e., directly overhead). The round-trip time to a data center anywhere on Earth would traverse this link four times, resulting in an absolute minimum round-trip time of 7 ms (even with zero interface and queuing delays). However, since satellites are mostly not located directly overhead of both the user and the satellite ground station, the theoretical minimum round-trip times for a satellite at 550 km will vary between 7 and 17 ms, depending on the relative position of the satellite, the user, and the ground station, assuming a minimum elevation angle of 25 degrees (see Figure 6). Thus, orbit altitude is a determining factor for the minimum latency that a constellation can achieve. The non-terrestrial contribution to the round-trip propagation delay could in principle be reduced to ~10 ms by lowering orbit altitudes to ~300 km.[10] Note that the terrestrial contribution to the round-trip propagation delay is ~1 ms/100 km distance covered.

Terrestrial networks have an advantage in terms of latency compared to the satellite networks because they don't face this minimum non-terrestrial contribution of 10+ ms to the propagation delay. Terrestrial networks can therefore offer round-trip times that are at least 10–20 ms lower than those provided by LEO satellite networks.

10 Starlink recently got permission to deploy new satellites at a low orbit altitude of ~350 km, referred to as Very Low Earth Orbit or "VLEO" (as opposed to the current "LEO" altitude of ~550 km) [5].

Overview of satellite and terrestrial network benchmarking

The differences in characteristics and capabilities of satellite and mobile networks are summarized in Table 2. Satellite broadband solutions and terrestrial networks have major differences in terms of spectrum, licensing, devices and radio technology. Satellite broadband can sometimes achieve performance comparable to the FWA connectivity provided by terrestrial networks. Satellite D2D connectivity to smartphones utilizes either existing mobile operators' spectrum or satellite spectrum (MSS), possibly using 3GPP radio technology, to complement terrestrial network coverage.

Table 2. Overview of some of the main characteristics of the satellite connectivity options considered in this publication for satellite broadband to fixed terminals and satellite D2D.

	Higher than 100 Mbps		Smartphones	
	5G Fixed Wireless Access	**Satellite broadband**	**5G terrestrial mode**	**Satellite Direct-to-Device (D2D)**
Service providers	Mobile operators	Satellite operators	Mobile operators	Satellite-mobile operator partnership
Spectrum	TDD spectrum (2-4 GHz) mm-wave (24+ GHz)	Satellite spectrum above 10 GHz	FDD + TDD spectrum at 0.6-3.5 GHz	FDD spectrum (mostly) at 0.6-2.6 GHz
Spectrum type*	Terrestrial	Satellite	Terrestrial	Both terrestrial and satellite
User data rate	Higher than 100 Mbps	Higher than 50 Mbps	Higher than 100 Mbps	Lower than 10 Mbps**
User device	Indoor and outdoor 5G modem	Outdor dish antenna	4G/5G mobile device	
User device cost	Low $100	~$400	$100-1000	
Radio technology	3GPP	Proprietary or 3GPP (Rel-18/19)	3GPP	3GPP or proprietary
MNO viewpoint	Key growth segment	**Competes wih 5G FWA**	Mainstream service	**Complementary to terrestrial mobile network**

* Terrestrial specrum is auctioned for exclusive use. On the other hand, satellite spectrum is administratively allocate and, in principle, shared.
** Single-user D2D data rates upto 20 Mbps have been demonstrated. However, these will need to be shared by users spanning larger regions of hundreds of square kilometers, and don't reflect impact of cross-cell interference or frequency reuse schemes present in real deployments.

Satellite networks have a minimum cell size that is mainly determined by the frequency, the antenna directivity, and the orbit altitude. Satellite cell sizes are much larger than those of terrestrial networks, and satellite networks cannot readily increase capacity density in certain areas by deploying smaller cell sizes (as in terrestrial networks). Adding more satellites increases the total constellation capacity but does not help increase the maximum cell capacity density determined by the utilized bandwidth and the beam size on Earth. For D2D, the combination of large cell sizes and limited spectrum severely limits the achievable data rates compared to terrestrial 4G/5G mobile networks. With respect to latency, LEO orbits support round-trip times in the order of tens of ms. These are much lower than the hundreds of ms latencies experienced in traditional GEO satellite services but still higher than the latencies achievable in terrestrial mobile networks (due to the contribution of the non-terrestrial propagation delay in satellite networks).

In terms of cost and deployment aspects, there are some differences worth highlighting:

- The user terminals for broadband satellite connectivity require more complex receivers with beamforming antennas, which makes satellite CPEs more costly than terrestrial CPEs used for FWA.

- In terms of operating and capital expenses, satellite systems have the benefit of not incurring costs and practical challenges related to site acquisition, opex costs related to site rental, backhaul rental, and power consumption, as well as installing proper powering infrastructure (especially in rural areas). However, LEO satellites do have a limited lifetime of 5–10 years,[11] after which a replacement satellite needs to be launched to maintain service. This continuous process of "replenishing" satellites results in a significant opex cost a few years after the initial deployment of the LEO constellation. Satellite ground stations on Earth and the accompanying ground network also need to be maintained, though the number of required satellite ground stations is orders of magnitude lower than terrestrial base station sites. Starlink is estimated to operate ~150 ground stations around the globe.[12]
- A single LEO constellation can be used to service multiple geographical regions using the same satellites. A LEO constellation initially deployed to serve a particular region can relatively easily/quickly extend services to new regions without requiring major additional capex investments (except for the possible installation of satellite ground stations and the related ground network in the new regions).

After this high-level overview, we will benchmark the performance of satellite and terrestrial options in greater detail in the next two sections. We will combine our own estimations with existing benchmarking data from commercial and pre-commercial services. The first will compare satellite broadband connectivity with 5G FWA, and the second will compare satellite D2D with terrestrial 5G mobile networks.

11 This is significantly impacted by the atmospheric drag that LEO satellites experience due to their low orbit altitude, and their capability (fuel and thrust) to counter this effect. Eventually, this atmospheric drag causes the LEO satellites to crash into Earth.

12 Although Starlink does not disclose how many ground stations it operates, it is estimated to have ~150 of them across the world (of which ~50% in the US) [6].

Satellite fixed broadband vs. 5G FWA

Both satellite fixed broadband and 5G FWA have seen rapid growth in recent years. Starlink is currently providing service to over 6 million subscribers across the globe of which roughly 2 million are in the US [7]. On the other hand, terrestrial 5G mobile networks have globally amassed over 50 million FWA subscribers over a similar time frame, and over 150 million when including 4G/LTE FWA subscribers as well [8].

We'll compare these two technologies along different dimensions (capacity, latency, and market pricing) and wrap up an outlook on how they might evolve in the near future.

Capacity benchmarking

This section aims to evaluate the capacity limits of both Starlink and the terrestrial FWA solution and specifically focuses on the capacity density limits in terms of Mbps per square kilometer. 5G FWA calculation assumes three different areas: urban with a 300 m cell range, suburban with 1 km, and rural with 3 km, each with three-sector base station configurations. The spectrum is assumed to be 100 MHz of TDD with a spectral efficiency of 6 bps/Hz. For mm-wave FWA, we assume 800 MHz of TDD spectrum and a spectral efficiency of 5 bps/Hz. The calculation shows the capacity achievable by a single 5G FWA operator. The traffic distribution assumes that 20% of the cells carry 50% of the traffic.

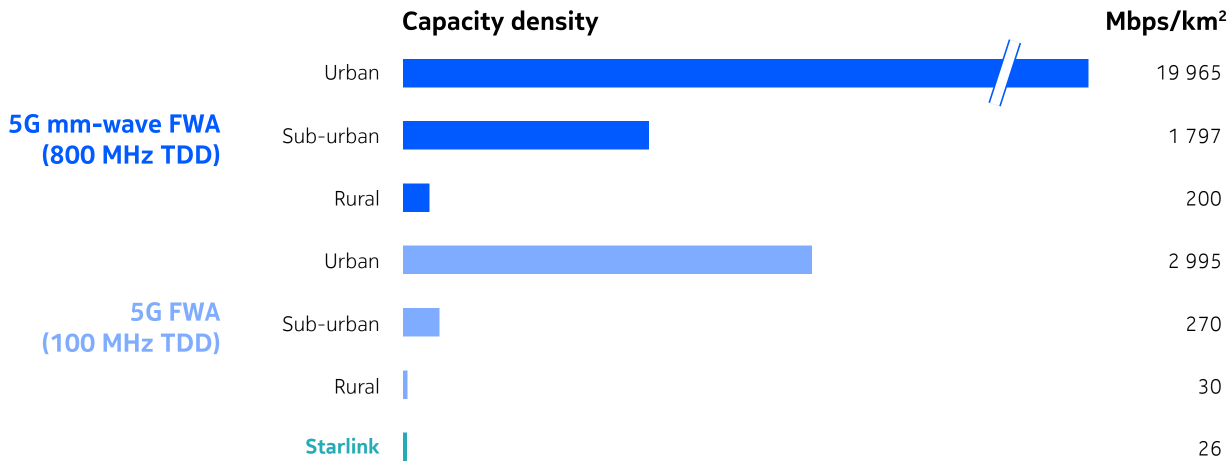
To calculate Starlink's capacity density, we assume the entire 2 GHz Ku spectrum band (10.7–12.7 GHz) and the corresponding maximum dual-polarization data rate are allocated to a single beam with an area of 380 km^2 on the Earth's surface [9]. The spectral efficiency for each polarization is assumed to be 5 bps/Hz corresponding to the reportedly highest 64-QAM modulation including overhead. However, we reduce the resulting "maximum" capacity density estimation by 50% because it's overly optimistic for several reasons:

- **Frequency reuse**—although it's not known exactly how Starlink operates, using signals with the same frequency in adjacent cells either increases self-interference or is directly avoided in practice using scheduling that leverages a certain frequency reuse scheme; both options unavoidably lead to a significant reduction in capacity density, for example, using a frequency reuse-3 scheme would lower the capacity density by 66%
- **Power flux limitations**—focusing two polarizations on a single spot requires lowering the transmit power by 3 dB to obey the maximum power flux density on the Earth's surface, which is limited by regulation
- **Scheduling overhead**—in practice, the Ku band is subdivided into smaller spectrum chunks (250 MHz) and two polarizations, which are dynamically scheduled in TDMA fashion across different Earth cells
- **Spectrum sharing**—the Ku-band satellite spectrum needs to be shared with other licensed satellite operators
- **Other services**—Starlink's constellation also supports additional services, other than residential broadband, that use some of its capacity.

Overall, the 50% reduction factor can still be considered optimistic. The resulting capacity densities are illustrated in Figure 7. Compared to Starlink's capacity density (~26 Mbps/km^2), single operator 5G FWA capacity density is >100x higher in urban areas (2995 Mbps/km^2), ~10x higher in suburban areas (270 Mbps/km^2), and comparable in the rural areas (30 Mbps/km^2). If 5G mm-wave is utilized, 5G FWA capacity density increases roughly tenfold (requiring a line-of-sight connection).

We can convert capacity density into user density by assuming a fixed-broadband consumer uses 500–600 GB/month, corresponding to an average busy-hour data rate of 4 Mbps in downstream. Using that, Starlink can support approximately seven subscribers/km², while urban 5G FWA can support over 700 subscribers/km² and 5G mm-wave over 4,000 subscribers/km². As mentioned before, Starlink's capacity density limitation is visible in some areas in the US, where an additional charge was introduced to limit the number of new users.[13]

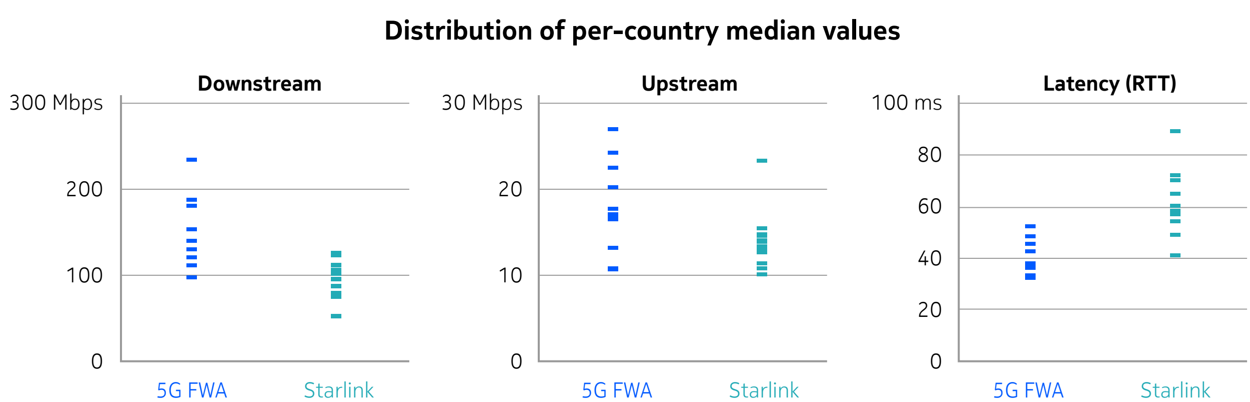
Figure 7: Broadband capacity density benchmarking between 5G FWA (single operator with 100 MHz, or 800 MHz mm-wave) and Starlink (Ku band). 5G FWA has a significantly higher capacity density in urban and suburban areas, while it is similar in rural areas.



Data rate and latency benchmarking

Figure 8 compares crowd-sourced speed test results from Ookla for commercial 5G FWA and Starlink in several European countries[14] and the USA. It shows the distribution of the per-country median downstream and upstream data rates, as well as the median round trip times. The trend indicates that the performance of current 5G FWA deployments is typically comparable or superior to that of Starlink.

Figure 8: The distribution of Ookla speed test data representing per-country median values from 5G FWA and Starlink services indicates that 5G FWA performance is typically comparable or superior to that of Starlink. Ookla data from several European countries and the United States [11].



13 Starlink support page mentions that "In areas with high demand, there is an additional one-time charge to purchase Starlink services" [10]
14 Austria, Finland, France, Germany, Italy, Poland, Romania, Spain, Sweden, and United Kingdom. Data from [11].

The average of the per-country median downstream data rates for 5G FWA is 149 Mbps vs. Starlink's 91 Mbps. In the upstream direction, 5G FWA achieves 18 Mbps vs. 14 Mbps for Starlink. Notably, 5G FWA data rates show a higher degree of variability compared to Starlink, probably attributable to significant differences in 5G signal quality and network loading across different countries.

5G FWA typically achieves a round-trip latency of 41 ms vs. 61 ms for Starlink, while the lowest values are 32 ms and 41 ms, respectively. These values are substantially larger than the theoretical minimum values due to the transport network architecture, the distance to the data center, and additional interface and queuing latencies along the end-to-end path. The latency variability is substantially larger for Starlink than for 5G FWA. This variance is probably due to country-dependent proximity and local density of satellite ground stations, as well as their respective proximity to data centers. The United Kingdom is the only country in the data set where Starlink achieves a lower median latency (41 ms for Starlink vs. 45 ms for 5G FWA).

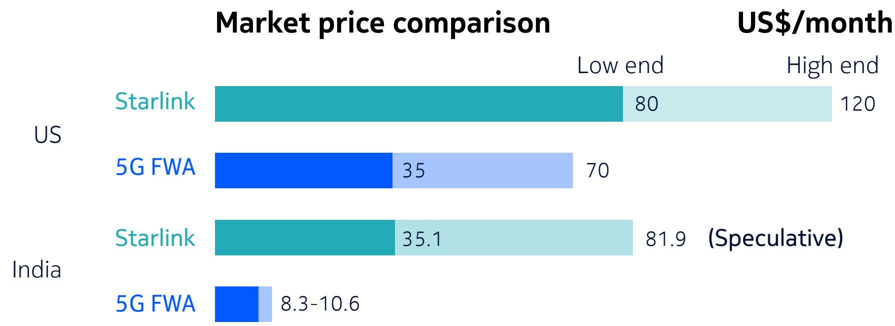
In other regions closer to the equator such as Africa, Starlink data rates are slightly lower. A recent Ookla report [12] focusing on sub-Saharan Africa reports median download data rates between 44.2 and 106.4 Mbps and upload data rates between 7.92 and 14.85 Mbps, depending on the country. It's notable that these downstream data rates outperform (terrestrial) fixed ISPs across Africa. However, median Starlink latency values (53-251 ms) are substantially higher than those of the fixed networks (13-111 ms). The lower Starlink data rates compared to more Northern regions could be attributed to the lower density of satellites orbiting the equator.

Market price benchmarking

This section shows a few global examples regarding current 5G FWA and Starlink market pricing, starting with the US market that has seen relatively advanced deployments of both technologies over the past years. In the US, there were 12 million 5G FWA subscribers and 2 million Starlink subscribers at the end of 2024. While both solutions have been available for consumers, the market uptake of 5G FWA has been significantly higher than that of Starlink. Beyond the performance superiority and lower energy consumption of 5G FWA user devices, another explanation could be the lower consumer pricing of 5G FWA compared to Starlink (see Figure 9). 5G FWA pricing—including the CPE—is $50/month and even starts at $35/month if bundled together with phone subscriptions. Starlink pricing is $80–120/month and had an average additional cost for the satellite receiver hardware price of ~$350 in 2024. Hence, where fiber or 5G FWA with good performance is available, there is little motivation to opt for Starlink.

But 5G prices and Starlink prices are, of course, country dependent. For example, in India the 5G FWA price point is $8–11. Starlink pricing is not available yet but is speculated to be around $35–82 [13], which would be clearly lower than in the US but still substantially higher than 5G FWA pricing in India. Additionally, Starlink customers also incur an additional cost for the Starlink satellite receiver.

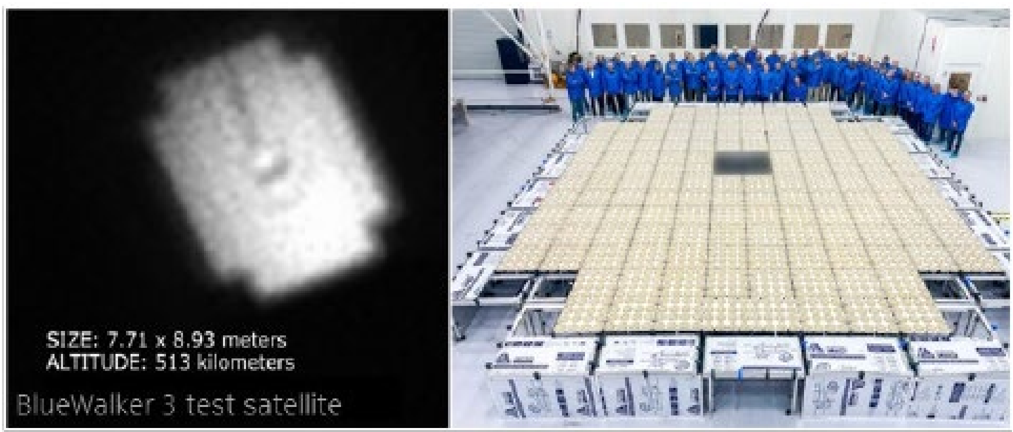
Figure 9. 5G FWA broadband services are most often lower-priced than Starlink within the same country. Note that the Starlink pricing in India is speculative, based on estimates [13], as the service is not yet commercially available.



Satellite smartphone connection (D2D) vs. 5G terrestrial

Satellites can also support a direct connection (D2D) to existing LTE/5G smartphones and IoT devices, i.e., without requiring a specific satellite phone or receiver hardware. There are multiple satellite initiatives already supporting D2D services, such as AST SpaceMobile, Lynk Global, and Starlink. Nokia is a supplier to AST SpaceMobile, whose Blue Walker 3 satellite is shown in Figure 10.

Figure 10. AST SpaceMobile's Blue Walker satellite dimensions are roughly 8x9 m, leveraging an RF phased array that measures a whopping ~64 m^2. It is the largest commercial phased array ever deployed on a LEO communications satellite so far. Image courtesy of AST.



Text-messaging D2D services are commercially available today and are expected to soon include support for voice and low-rate data communication as well. Current D2D services either leverage mobile satellite spectrum (e.g., Apple/Globalstar) or reuse terrestrial mobile spectrum from MNOs (e.g., AT&T/AST, T-Mobile/Starlink). AST SpaceMobile is collaborating with multiple mobile operators around the globe, including AT&T, Vodafone, Verizon, Bell Canada, MTN, Orange, Telefonica, and Telstra. Similarly, Starlink and Lynk Global also collaborate with multiple operators. The partnerships allow the satellite operators to reuse an operator's terrestrial spectrum to extend their network coverage by connecting existing 4G LTE and 5G devices via satellite. In those cases, the D2D satellite service effectively uses a portion of the terrestrial mobile FDD spectrum.

Capacity benchmarking

Recent demonstrations of AST SpaceMobile and Starlink use terrestrial FDD spectrum blocks of 5 MHz. For AST SpaceMobile, the cell sizes on Earth reportedly have a diameter of 48 km (low-band, i.e., sub-GHz), 24 km (mid-band), or 12 km (C-band around 3.7 GHz) [14]. For Starlink, D2D cell sizes have a diameter of ~50 km [15]. AST SpaceMobile demonstrated downstream peak data rates of 20 Mbps using 5 MHz [16], and Starlink demonstrated 17 Mbps using 5 MHz [17]. Hence, both operators achieved an impressive single-user spectral efficiency of roughly 3-4 bps/Hz. In the calculation below, we used a spectral efficiency of 2 bps/Hz for satellite D2D[15] to account for the impact of cross-cell interference and/or frequency reuse

15 A recent study collecting crowdsourced mobile network data of Starlink D2D has shown mean and median spectral efficiencies of 0.79 and 0.64 bps/Hz, respectively (measured in the US between October 2024 and April 2025). In March 2025, the FCC allowed a 10 dB increase in out-of-band emissions (i.e., interference limit to other systems), thanks to which Starlink could increase its transmit power, which would increase those values to 1.17 and 1.05 bps/Hz [19].

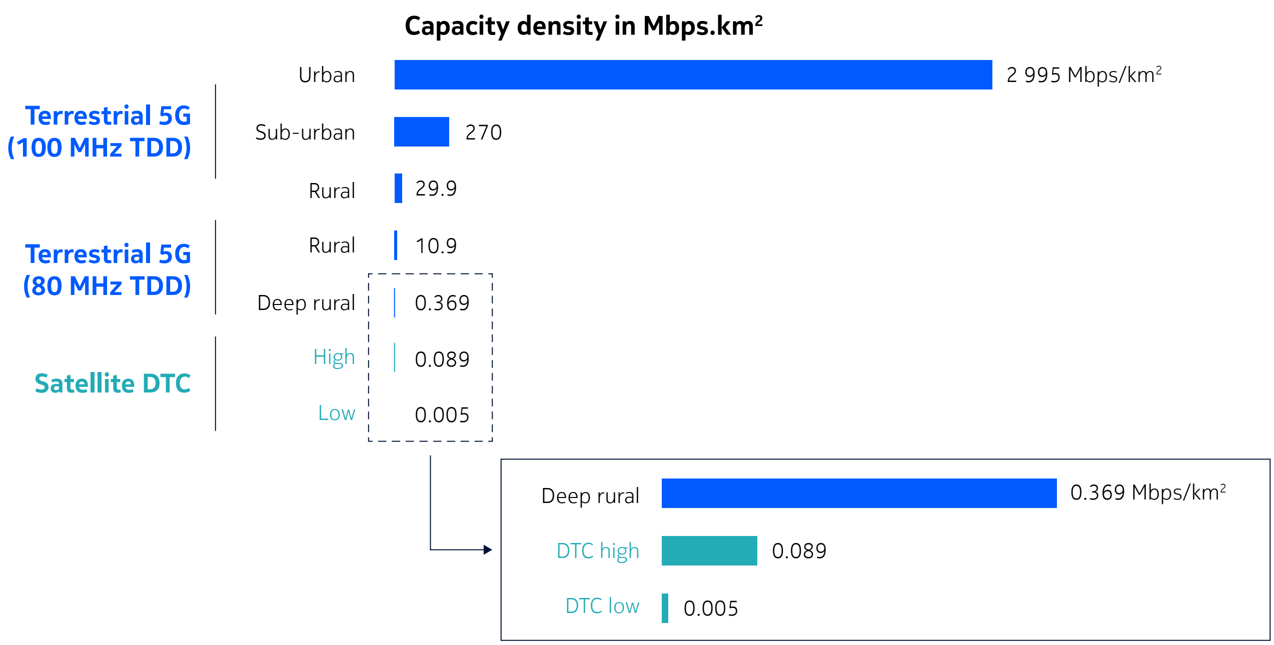
(the typical spectral efficiency achieved in terrestrial rural 5G FDD networks is also 2 bps/Hz). We model two satellite D2D cases:

1. 'High'—20 MHz spectrum and 450 km² cell size (24 km diameter)
2. 'Low'—5 MHz spectrum and 2000 km² cell size (50 km diameter).

For the terrestrial network, we complement our earlier TDD modeling (see 5G FWA) with an FDD-based terrestrial deployment for rural and deep rural areas. For rural areas, we assume 80 MHz of FDD spectrum, a spectral efficiency of 2 bps/Hz, and an inter-site distance of 3 km. For deep rural areas, we assume a higher inter-site distance of 10 km while keeping other parameters the same.

The resulting D2D capacity density shown in Figure 11 is more than 100x lower than that of rural terrestrial 5G FDD (0.089 Mbps/km² vs. 10.9 Mbps/km²), and 4–74x lower than that of deep rural 5G FDD (0.005–0.089 Mbps/km² vs. 0.369 Mbps/km²). Compared to 5G TDD in suburban and urban areas, this ratio further increases to more than 3,000x and 30,000x, respectively (0.089 Mbps/km² vs. 270–2995 Mbps/km²).

Figure 11. A comparison of the capacity densities of terrestrial 5G and satellite D2D shows that D2D will not be able to offer capacity densities anywhere close to terrestrial 5G networks in urban or suburban areas.



Thus, although the LEO satellite phased array technology formidably bridges a very challenging space-to-Earth link, D2D capacity densities are limited due to the large satellite cell size and limited spectral resources. Nevertheless, the double-digit Mbps single-user data rates demonstrate significant progress in the field, making D2D suitable for extending coverage to areas that lack terrestrial coverage today.

Link budget benchmarking and field measurements

Besides spectrum limitations, achievable D2D data rates can also be limited by the large distance between the end user and the satellite orbiting hundreds of kms above the Earth's surface. At a frequency of 2 GHz, the free space path loss amounts to 152.4–158.5 dB, assuming a propagation distance between 500 and 1,000 km considering the variation in the satellite elevation angle. This further increases for higher frequencies,[16] as the path loss is proportional to the frequency squared. Such path losses are very high considering the maximum allowed path loss in 5G systems. The typical base station reference signal transmission power in 5G is 20 dBm, and the practical minimum signal level is somewhere between -124 and -120 dBm, which enables a maximum path loss of just over 140 dB without antenna gains. Some interference and fading margins are needed, and therefore, the practical maximum allowed path loss is 120 to 130 dB in 5G networks, which is far below the path loss attenuation solely based on the distance between the mobile UE and the satellite. However, it is possible to achieve a voice and data connection between the smartphone and the satellite thanks to the high satellite antenna gains, more than 40 dBi, which increase the total allowed path loss to 160-170 dB, exceeding the free space loss of 152.4–158.5 dB. The calculations indicate that there is limited room for additional indoor losses (approximately 12 dB) in the D2D link budget, and the data rate will be limited to relatively low values.

The Signal Research Group recently published early measurements of Starlink's D2D service in T-Mobile's USA network [19], currently limited to only messaging. In terrestrial networks, messages are always delivered within three seconds. The measurements show that roughly 52% of D2D messages are also delivered within three seconds. However, 20% of D2D messages still have a delivery time of more than 45 seconds. The average signal level was -117 dBm, and P10/median/P90 levels were -127.2/-116/-109.5 dBm). The variation in processing delays and low receive signal values indicates that there is still some progress required to be able to properly support voice and data services. The measured signal levels are not far from the absolute minimum values required for the radio link to function, confirming there is little margin for coping with additional indoor penetration loss.

Example commercial offerings: T-Mobile and One NZ

D2D services are already commercially available on a few mobile networks around the world. Two examples are T-Mobile USA and One New Zealand, both leveraging Starlink. Another example is Verizon, which leverages Skylo. Currently, they only provide a D2D messaging service.

One NZ has made the service available to certain payment plans and eligible phones that have so far been thoroughly tested [20] (e.g., a range of Apple, Samsung, and Oppo models). More phone models are to be supported over time. One NZ is planning to charge $3/month for the satellite connections if they are not included in the plan. One NZ recently increased its spectrum resources allocated to D2D from 5 to 15 MHz, after experiencing a substantial uptake since commercial launch and to enable offering additional services including data and IoT [21].

T-Mobile launched a commercial D2D service in August 2025, following a free and open-for-everyone beta service that ran until July 2025. The "T-Satellite" service is included in certain higher-end plans, and available as a separate subscription for $10/month [22].

Verizon also launched a messaging service but leveraging Skylo. Skylo operates according to the 3GPP Rel-17 Narrowband IoT (NB-IoT) standard and uses existing GEO satellites from satellite operators like Viasat, rather than LEO satellites. Verizon doesn't charge extra for the service, but it's currently limited to select Android smartphones [23].

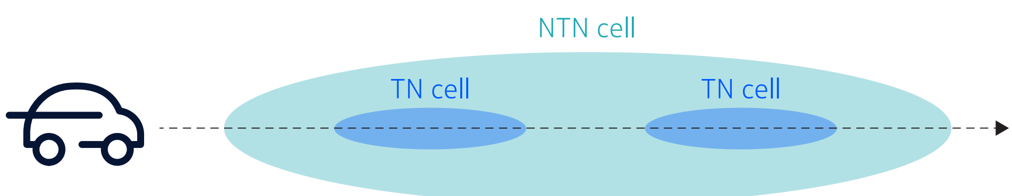
16 Attenuation through other mechanisms also increases for higher frequencies (e.g., atmospheric absorption, rain attenuation).

Terrestrial and satellite network mobility

Users in terrestrial mobile networks continuously transfer their smartphone's network connection from one mobile base station to another as they move around. In NTN, mobility is additionally triggered by the high-speed movement of the satellites themselves (i.e., handovers between subsequent satellites covering the same cell). Initial work in 3GPP Rel-17 focused on enabling smooth handovers between different satellites of the same constellation (intra-NTN), where UEs need in a timely manner, to adapt to the different position/speed/direction of the next satellite, so they can apply the appropriate timing and Doppler compensation to its signals. In pre-Rel-17 D2D deployments like AST and Starlink, this compensation is handled by the network, as the smartphone is unaware of whether it is connected to a terrestrial base station or a satellite.

The importance of service continuity is especially relevant when users continuously transition between the terrestrial and the satellite network like, for example, on roads with discontinuous coverage from terrestrial networks[17] (see Figure 12). Proper interworking between TN and NTN is crucial for several reasons. Aspects like spectrum reuse and the related interference management need to be properly coordinated across TN and NT, especially when both are using the same spectrum. Services should preferably continue uninterrupted as users transition between TN and NTN, requiring seamless mobility between them.

Figure 12. A car driving through a sparse TN coverage area is a prime example of how seamless TN–NTN mobility is crucial to the user experience.



The satellite operator can use its own dedicated mobile core and leverage regular mobility procedures to transition the user between the satellite network and the terrestrial network. It is possible to support either light weight integration or tight integration between TN and NTN. Mobility with seamless service continuity can be achieved by a tighter integration between the satellite and terrestrial core. Mobility could result in service disruption in case of loose integration due to a change in the anchor IP address. In a two-core setup, the change in IP address can be avoided by either leveraging tunneled interfaces between the UPFs of the two cores during handovers (N9 interface), or by the target RAN node connecting to the anchor UPF directly. Link setup time—which also impacts service continuity—can be reduced by having terrestrial and satellite cells share information regarding each other to facilitate mobility and handovers. For example, a TN cell can broadcast nearby satellite ephemeris information in terrestrial System Information Blocks (SIBs). Or an NTN cell can broadcast properties of TN cells within its coverage area, such that UEs can transition to them more swiftly (even while still in coverage of the NTN cell). Such NTN features were introduced in 3GPP Rel-18.

17 According to the European Space Agency (ESA), the quality and availability of network coverage are inconsistent, with drivers on major European roads experiencing approximately 12.4% of their travel time without connectivity, especially in sparsely populated rural areas [24].

Benefits of NTN for terrestrial operators

As shown in the previous section, D2D services offer an effective solution to expand mobile coverage to remote areas where terrestrial infrastructure is challenging or economically unfeasible to deploy. This includes mountains, lakes, and other hard-to-reach locations. NTN D2D should be viewed as a complementary rather than a competitive solution for terrestrial operators, as it cannot compete with the user experience provided by terrestrial mobile networks:

1. D2D capacity density is relatively low due to the large cell sizes and limited spectrum
2. D2D per-user data rates are lower due to the poorer link budget
3. Indoor coverage is limited due to challenging link budgets, owing to the large distances to the satellite
4. Spectrum commonly supported by user devices is currently controlled by licensed terrestrial mobile operators, who are not expected to dedicate large portions of their valuable spectrum resources. Future use of satellite spectrum—subject to device adoption—is possible but also faces limitations (see Section 7.2).

NTN also enables other benefits for terrestrial mobile operators such as network resilience, disaster recovery, IoT connectivity, mobile backhaul, and, generally, providing a new tool in their toolbox to solve problems more efficiently.

Increasing network resilience

By integrating NTN backup links, operators can enhance the resilience and reliability of their networks. Satellites and other non-terrestrial platforms can serve as backup communication paths in case of terrestrial network failures. As the capacity of NTN is smaller than that of terrestrial networks, the backup functionality could provide prioritized access to critical services such as public safety.

Improved disaster recovery

In the event of natural disasters or emergencies that disrupt terrestrial infrastructure, NTN can provide critical communication services for disaster response and recovery efforts. Satellite networks have already proven their value during natural disasters in the US and New Zealand. Other NTN platforms, like drones, can also be leveraged to put up temporary terrestrial 4G/5G base stations that, themselves, might use satellite backhaul (e.g., AT&T's flying Cell on Wings or COWs).

IoT Connectivity

NTN is well suited for connecting IoT devices in remote locations, such as environmental sensors, agricultural equipment, and IoT for maritime applications. 3GPP's NB-IoT provides a uniform technology platform across TN and NTN to seamlessly connect IoT devices moving in and out of coverage (e.g., agriculture) and to enable uniform and global IoT coverage (e.g., global logistics). Notably, Skylo also leverages 3GPP NB-IoT over GEO satellites for messaging services to smartphones (cf. Verizon partnership [23]).

Mobile backhaul

In areas without terrestrial infrastructure, mobile base stations can be backhauled through satellites. This is especially beneficial for remote base stations where power infrastructure is more readily available than connectivity (including microwave backhaul) or as backup for failures of the terrestrial backhaul.

A new tool in the operator's network-design toolbox

For certain applications and regions, NTN can be more cost-effective than deploying extensive terrestrial infrastructure, particularly in sparsely populated or geographically challenging areas. By leveraging NTN, terrestrial operators can enhance their service offerings and expand their market reach.

Future technology evolution

Both satellite and terrestrial communication technologies will further evolve their capabilities. In this section, we will examine how future satellite constellations can increase their capacity and reduce their limitations. In the second part, we zoom in on the spectrum and consider how spectrum will and could be expanded for both satellite and terrestrial networks.

Technical improvements in satellite networks

As discussed in the section “Satellite network capacity”, performance of a satellite network can be limited by the total constellation capacity or by the local capacity density. Simply launching more satellites will increase the total constellation capacity, as long as there are spots on Earth that are not always covered by a satellite already. But for a single spot on Earth, it’s the capacity density that is the limiting factor, which is determined by the service beam spectrum and beam size.

Exploiting spatial diversity

One way to increase the local density limit for satellite broadband is to leverage the directivity of the VSAT phased arrays. Multiple co-frequency, co-polarization beams—each from a different satellite—could be directed to the same cell on Earth to increase that cell’s capacity density. The method, however, requires the receive antenna directivity on the user terminal to suppress all but one of the beams coming from different spatial angles. A similar concept, known as GSO arc avoidance, is used to avoid interference from new LEO satellites to existing GEO services that use the same spectrum.

Achievable gains would, however, be limited by self-interference that is inevitably caused by the finite antenna directivity. Moreover, current regulation limits the number of so-called co-frequency beams (NCo) to one to limit interference to GSO services from other satellite operators [25].

Note that for D2D, with receivers that have isotropic antennas, it is not possible to exploit this potential gain from spatial diversity. Another way to increase capacity density is to reduce the beam size on the Earth’s surface, which can be achieved by orbiting satellites at a lower altitude and/or generating a narrower beam.

Deploying constellations at lower orbit altitudes

Deploying satellite constellations in lower orbital altitudes reduces the cell size on Earth because the beam area is proportional to the square of the orbit altitude. Low-altitude LEO satellite orbits at 250–350 km are also referred to as Very Low Earth Orbits (VLEO). Starlink will exploit lower orbit altitudes in its second-generation VLEO constellation. The first-generation LEO constellation orbits at an altitude of ~550 km. But Starlink recently received FCC authorization [26] to orbit its second-gen VLEO constellation at a significantly lower altitude of ~340 km.[18] Lowering the orbit altitude from 550 km to 340 km reduces the spot beam size on Earth by ~60% hence boosting capacity density by ~150%.

Other benefits of VLEO are a lower latency (cf. section “Satellite network latency”), and the orbit being “self-cleaning,” due to the increased atmospheric drag causing debris to crash or burn in a much shorter time. The flip side of lower orbit altitudes is that VLEO satellites face a reduced lifetime (more atmospheric drag) and more satellites are needed to obtain continuous coverage.

18 The request faced extra scrutiny due to the potential harm it might cause to the International Space Station, which orbits at a higher altitude of ~410 km.

Narrower beams

The larger the phased array, the narrower the beam it can generate and, the lower the communication frequency, the larger the phased array needs to be because dimensions scale with the wavelength. Operating at higher frequencies also allows for the creation of narrower beams without increasing the outer dimensions of the satellite phased array. This is why the diameter of AST's beam size on Earth is smaller for higher than for lower frequencies.

Current AST satellites are sized at ~64 m^2, and next-generation satellites will boast even larger phased arrays on satellites of ~223 m^2, i.e., more than 3x larger than current satellites [27]. Assuming an efficiency of 80% and a frequency of 880 MHz, a phased array of that size can in theory achieve a very high antenna gain of ~43 dBi [28]. As the spot beam area on Earth is inversely proportional to the size of the satellite phased array, doubling to 446 m^2 would halve the spot beam area to ~134.5 km^2. At least one impediment for further increasing the phased array size—besides the engineering challenges of the array itself—would be satellite launch fairing volume limitations[19] due to the corresponding increase in satellite size. Compared to SpaceX's Falcon 9 rocket, the next-generation SpaceX Starship rocket is expected to increase the launch volume by roughly 7x [29].

Alternative spectrum for NTN

The other option for increasing capacity density is to use more spectrum.

Satellite broadband spectrum

The capacity provided by LEO satellites will increase by adopting higher frequencies, like Starlink's plans to leverage V-band spectrum for the satellite-to-terminal link. Besides the additional V-band spectrum (37.5–42 GHz), the higher frequencies also enable the spot beam area to be reduced to ~52 km^2 (vs. ~379 km^2 for Ku-band). The combined effect would increase the maximum capacity density of Starlink broadband by an order of magnitude (from 26 Mbps/km^2 to ~450 Mbps/km^2), rivalling current rural 5G FWA mm-wave capacity densities of 200 Mbps/km^2 (cf. Figure 7). However, V-band communication will also be subject to more link variability due to its increased sensitivity to weather conditions (e.g., rain). On the other hand, the capacity of terrestrial mobile networks is also expected to increase with new spectrum (e.g., 7 GHz) and the adoption of 6G technology. We estimate that the capacity of 6G will also be ~10 times higher than that of 5G shown in Figure 7, achieved by using two to four times more spectrum that has a two to four times higher spectral efficiency.

3GPP Rel-18 and Rel-19 extended standard support to include Ka- and Ku-bands, paving the way for a satellite broadband service using a 3GPP-standard waveform (as opposed to Starlink or Amazon Kuiper, which use proprietary waveforms).

D2D spectrum

Finding more spectrum for D2D is challenging, as it needs to be relatively low frequency. As mentioned previously, the Apple/Globalstar partnership uses MSS spectrum instead of terrestrial spectrum. Other examples include Verizon's partnership with Skylo, which offers D2D for select Android phones using MSS spectrum to connect to partner GEO satellites [30], and the recent AST/Ligado commercial agreement that allows AST to use Ligado's L-band MSS spectrum in the US and Canada [31]. Starlink has submitted requests to the FCC for access to MSS spectrum bands; at the time of writing (Aug 2025), these request have been unsuccessful.

19 The protective shell that encases a satellite during the launch phase.

There are three primary MSS bands that are currently being considered for D2D at 3GPP (see Table 3) [32]:

- The “2 GHz band” (n256) around 2 GHz
- L-band GEO spectrum (n255), around 1.6 GHz
- The “Big LEO band” (n254) around 1.6 (uplink) and 2.5 GHz (downlink).

Table 3: Satellite spectrum bands that can be considered for D2D service. All these bands are already licensed—and used by—different satellite operators. Commercial agreements between these existing spectrum holders and D2D players could be a pragmatic way forward.

Operating band	Uplink Freq. range (MHz)	Downlink Freq. range (MHz)	Bandwidth (MHz)
256	1980-2010 (RoW) 2000-2020 (NAM)	2170-2200 (RoW) 2180-2200 (NAM)	30 (RoW) 20 (NAM)
255	1626.5-1660.5	1525-1559	34
254	1610-1626.5	2483.5-2500	16.5
253*	1668-1675	1518-1525	7

* specified for IoT by 3GPP

A fourth band around 1.6 GHz, n253, is specified for IoT by 3GPP. Some of these MSS bands have up to ~30 MHz of spectrum in both uplink and downlink directions. However, these bands are also already licensed to, and used by, different satellite operators. The omnidirectional antennas on user devices and the anticipated wide geographic spread of D2D users introduce challenges for co-frequency sharing mechanisms to enable band sharing with existing services (e.g., arc avoidance, priority-sharing). Either the new D2D service might need to suppress its transmit power to an extent that makes it non-workable, otherwise, allowing higher transmit powers might impact users of existing MSS services [32]. The Apple/Globalstar and AST/Ligado examples seem to indicate that commercial agreements between MSS spectrum holders and D2D players could be a pragmatic way forward to enable adoption of MSS spectrum in D2D services. The AST/Ligado agreement could enable 40 MHz of spectrum for D2D, which would be twice the assumed 20 MHz in our earlier D2D capacity density modeling for the ‘high’ case.

The main drawback of using satellite spectrum is the lack of device support. For device manufacturers like Apple, this is less of an issue. Mobile operators, however, typically have less control over the devices used for their connectivity services. Over time, this deployment hurdle for using D2D spectrum could be reduced by increasing device support driven by 3GPP standards and demand from mobile operators towards device and chipset manufacturers.

Summary and recommendations for mobile operators

Satellite communication is addressing increasingly wider customer segments, and its growth is expected to be further propelled by cost reductions due to advances in launch capabilities and increasing production volumes.

Today, Starlink can provide a fixed satellite broadband connection that can achieve a user performance like that of 5G FWA and is immediately available across a whole country. This makes for an attractive solution in areas without access to fiber or 5G FWA. On the other hand, 5G FWA is capable of much higher capacity densities (Mbps per km^2). This makes 5G FWA a much more appropriate solution for areas with higher user densities. Starlink's maximum capacity density does not increase by launching more satellites, because that is determined by the satellite antenna size and spectrum. Starlink's capacity density is expected to roughly increase tenfold when introducing support for V-band spectrum, by virtue of the additional spectrum and smaller beam spot sizes.

Direct-To-Device (D2D) services are starting to be commercially deployed across the globe, able to support low data-rate services for consumers as well as emergency and public safety connectivity services. Current D2D services either leverage mobile satellite spectrum (e.g., Apple/Globalstar) or reuse terrestrial mobile spectrum (e.g., AT&T/AST and T-Mobile/Starlink). As terrestrial mobile spectrum is a scarce resource, additional satellite spectrum-based solutions are expected to emerge as well. D2D can be considered as a solution for mobile operators to complement their terrestrial network coverage and is expected to be an integral part of 6G mobile networks from day one.

We recommend the following actions for mobile operators:

1. Satellite broadband competition to 5G FWA services
   - **Expand 5G FWA service and coverage** to additional towns and villages as soon as possible to pre-empt market share capture from satellite broadband's increasing capabilities (e.g., addition of V-band). Once a customer has a 5G FWA connection with good performance (and a lower cost than satellite broadband), there is little motivation for switching
   - **Optimize 5G FWA performance and upgrade the network** accordingly to maintain high customer satisfaction and avoid customer churn
2. D2D serves as a complement to the 5G consumer mobile service
   - **Pilot D2D service providers** to experience practical performance in local conditions
   - **Work out a D2D spectrum strategy** based on an evaluation of your own spectrum assets and network coverage characteristics
   - **Leverage D2D for smartphone customers** by providing connectivity beyond the coverage of terrestrial networks as an opportunity to increase ARPU
3. Evaluate the other opportunities brought about by NTN
   - **IoT and public safety use cases** leveraging extra coverage from satellite connectivity (e.g., IoT for agriculture, nationwide and seamless connectivity services for public safety, integrated backup connectivity solutions for critical utilities and enterprises)
   - **This new tool in the operator's toolbox** allows to explore new solutions to old and new problems such as mobile backhaul, and network design for increasing coverage

Abbreviations

3GPP	Third Generation Partnership Project
AI	Artificial Intelligence
AST	Advanced Space Technologies
COW	Cell on Wings (AT&T)
CPE	Customer Premises Equipment
DTC	Direct-to-Cell
D2D	Direct-to-Device
FDD	Frequency Division Duplex
FSS	Fixed Satellite Services
FWA	Fixed Wireless Access
GEO	Geostationary Earth Orbit
GSO	GeoSynchronous Orbit
IoT	Internet of Things
IRIS2	Infrastructure for Resilience, Interconnectivity and Security by Satellite
ISP	Internet Service Provider
LEO	Low Earth Orbit
LTE	Long Term Evolution
MNO	Mobile Network Operator
MSS	Mobile Satellite Services
NB-IoT	Narrowband IoT
NCo	Co-frequency beams
NTN	Non-Terrestrial Network
SIB	Signal Information Block
TDD	Time Division Duplex
TN	Terrestrial Network
VLEO	Very Low Earth Orbit
VSAT	Very Small Aperture Terminal

References

[1] Mobile Experts, “Satellite Broadband 2025,” Mobile Experts web site, Jan 2025. Online: https://mobile-experts.net/reports/p/satellitebroadband25

[2] Singh, M. and Singh J., “India backs Musk in satellite spectrum allocation row,” Tech Crunch, 15 Oct 2024. Online: https://techcrunch.com/2024/10/15/india-backs-musk-in-satellite-spectrum-allocation-row/

[3] Starlink, “Progress 2024: Connecting the unconnected,” Starlink Presentation, 1 Jan 2025. Online: https://www.starlink.com/public-files/starlinkProgressReport_2024.pdf

[4] Starlink, “My region is at capacity or shows as “sold out” on the availability map. What does that mean?” Starlink web site, viewed 19 Aug 2025. Online: https://www.starlink.com/support/article/240ac933-68ce-00dd-d8ec-0d5bf5816f3d

[5] FCC Order and Authorization, “Request for Deployment and Operating Authority for the SpaceX Gen2 NGSO Satellite System”, DA 24-1193, November 2024.

[6] Starlink Installation Pros, “Starlink Ground Station: Backbone of Satellite Internet,” Starlink Installation Pros web site, 28 Jun 2024. Online: https://starlinkinstallationpros.com/starlink-ground-station-backbone-of-satellite-internet

[7] Supan, J., “Starlink Just Passed 2 Million US Subscribers. But Can It Keep Up With Users’ Needs? CNET, 17 Jul 2025. Online: https://www.cnet.com/home/internet/starlink-just-passed-2-million-us-subscribers-but-can-it-keep-up-with-users-needs/

[8] Ericsson, Ericsson Mobility Report, Ericsson web site, Nov 2024. Online: https://www.ericsson.com/4adb7e/assets/local/reports-papers/mobility-report/documents/2024/ericsson-mobility-report-november-2024.pdf

[9] Pekhterev, S., “The Bandwidth Of The StarLink Constellation…and the assessment of its potential subscriber base in the USA,” SatMagazine, Nov 2021. Online: http://www.satmagazine.com/story.php?number=1026762698

[10] Starlink, “What is a demand surcharge?” Starlink web site, viewed 20 Aug 2025. Online: https://www.starlink.com/support/article/63d885d3-c269-21f9-69d6-3ed1b2fd18e9

[11] Kehoe, L., “Starlink Shines in Europe as Constellation Investments Boost Performance,” Ookla, 5 Feb 2025. Online: https://www.ookla.com/articles/starlink-europe-q1-2024

[12] Kehoe, L. “Connecting Africa: The Performance and Impact of Starlink’s Satellite Internet,” Ookla, 13 May 2025. Online: https://www.ookla.com/articles/starlink-ssa-q1-2025

[13] Haris, M., “Starlink Price In India: How Much Will Starlink’s Satellite Communication Cost To Indian Users?” News 18, 8 May 2025. Online: https://www.news18.com/business/starlink-price-in-india-how-much-will-starlinks-satellite-communication-cost-to-indian-users-9328382.html

[14] Jackson, D., “‘Life-saving technology’: AST SpaceMobile CEO outlines capabilities of direct-to-smartphone LEO satellite service,” Informa, Urgent Communications, 9 Apr 2021.

[15] FCC Filing, “SpaceX Gen2 Direct-to-cellular system – Attachment A: Technical information to supplement Schedule S”, February 2023.

[16] Stepanek, L., “Vodafone Agreement with AST SpaceMobile Enables Space-based Cellular Broadband Service,” Telecompetitor, 11 Dec 2024. Online: https://www.telecompetitor.com/vodafone-agreement-with-ast-spacemobile-enables-space-based-cellular-broadband-service/

[17] Musk, E., “SpaceX just achieved peak download speed of 17Mb/s from satellite direct to unmodified Samsung Android phone,” X post, 2 Mar 2024. Online: https://x.com/elonmusk/status/1764032892663906313

[18] Garcia-Cabeza, J., et al., “Direct-to-Cell: A First Look into Starlink’s Direct Satellite-to-Device Radio Access Network through Crowdsourced Measurements,” arXiv: 2506.00283v5, 13 Jul 2025. Online: https://arxiv.org/abs/2506.00283v5

[19] Signal Research Group, “5G: The Greatest Show on Earth, A Benchmark study of the T-Mobile-Starlink Messaging Service,” Signals Ahead v48, 11 Feb 2025. Online: https://signalsresearch.com/issue/5g-the-greatest-show-on-earth-48/

[20] One NZ, “One NZ Satellite is here,” One NZ web site, viewed 20 Aug 2025. Online: https://one.nz/why-choose-us/satellite/#eligible-phones

[21] Zang, S. (SpaceX), “FCC Notification - NZ Update,” SCRIBD, 29 Jul 2025. Online: https://www.scribd.com/document/895202237/FCC-Notification-NZ-Update-1

[22] T-Mobile, “T-Satellite is here. Never miss a message.” T-Mobile web site, viewed 20 Aug 2025. Online: https://www.t-mobile.com/coverage/satellite-phone-service

[23] Verizon, “Saltellite SOS and messaging FAQs,” Verizon web site, viewed 20 Aug 2025. Online: https://www.verizon.com/support/satellite-faqs/

[24] European Space Agency, “ESA supports the development of Ubiquitous, reliable and secure connectivity solutions for the car of the future,” Connectivity and Secure Communications (CSC) web site. Viewed 20 Aug 2025. Online: https://connectivity.esa.int/automotive

[25] FCC Order and Authorization, “Request for Orbital Deployment and Operating Authority for the SpaceX Gen2 NGSO Satellite System”, Dec 2022 (IBFS File Nos. SAT-LOA-20200526-00055 and SAT-AMD-20210818-00105).

[26] FCC, “Order and Authorization, DA 24-1193,” 26 Nov 2024. Online: https://docs.fcc.gov/public/attachments/DA-24-1193A1.pdf

[27] AST & Science, LLC., “Application for experimental authority to launch and operate the FM1 NGSO satellite,” FCC application file no. 0284-EX-CN-2025, 26 Feb 2025. Online: https://apps.fcc.gov/els/GetAtt.html?id=371448&x=

[28] Andrews, J. G., Humphreys, T. E. and Ji, T., “6G Takes Shape,” IEEE BITS the Information Theory Magazine, 4:1, pp. 2-24, Mar 2024, doi: 10.1109/MBITS.2024.3504521. Online: https://ieeexplore.ieee.org/document/10763455

[29] Law, A., “The definitve guide to Starship: Starship vs Falcon 9, what’s new and improved? Everyday Astronaut, 6 Nov 2020. Online: https://everydayastronaut.com/definitive-guide-to-starship/

[30] Rainbow, J., “Verizon to bring satellite connectivity to Android phones this fall,” SpaceNews, 29 Aug 2024. Online: https://spacenews.com/verizon-to-bring-satellite-connectivity-to-android-phones-this-fall

[31] Rainbow, J., “AST SpaceMobile strikes spectrum deal amid Ligado Networks bankruptcy,” SpaceNews, 6 Jan 2025. Online: https://spacenews.com/ast-spacemobile-strikes-spectrum-deal-amid-ligado-networks-bankruptcy

[32] TMF Associates & Summit Ridge Group, “Spectrum for Emerging Direct-to-Device Satellite Operators”, Jan 2025. Online:https://summitridgegroup.com/wp-content/uploads/D2D-White-Paper-SRG-TMF-Final.pdf

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