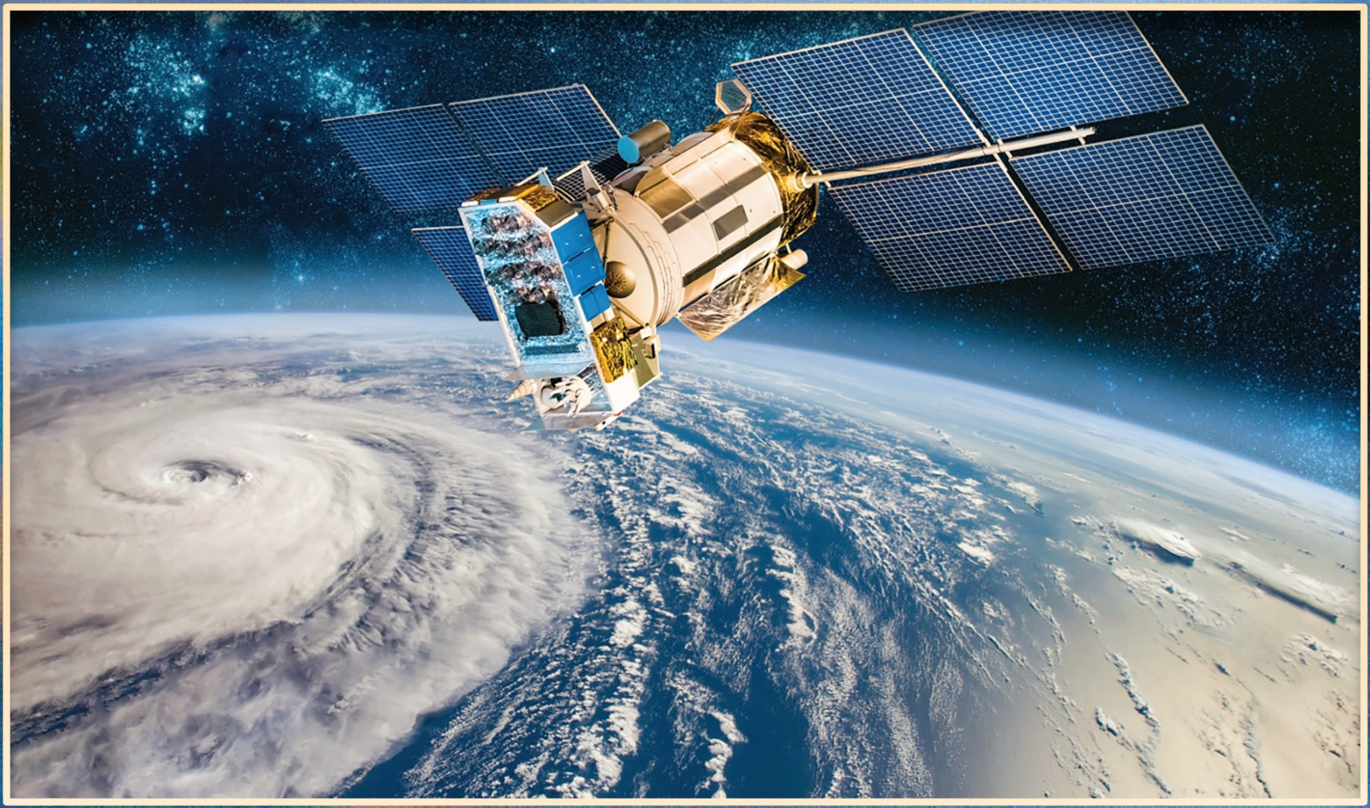
HOW NON-TERRESTRIAL NETWORKS ARE TRANSFORMING MOBILE COMMUNICATIONS



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Non-Terrestrial Networks

System operators are looking to non-terrestrial networks (NTN) to significantly expand the reach of traditional terrestrial or earth-based wireless networks. While NTNs have already impacted mobile communications over the last 30 years, they now appear poised to bridge the digital divide by providing ubiquitous communication services to remote and rural areas.

NTNs consist of various space-borne and aerial communication networks, including geostationary (or geosynchronous equatorial) orbit (GEO), medium-Earth orbit (MEO), low-Earth orbit (LEO) satellite constellations, High Altitude Platform Systems (HAPS), Low Altitude Platform Systems (LAPS), and air-to-ground (A2G) networks.

With NTN elements and components evolving to become an integral part of the future 6G wireless network, NTN is growing in importance owing to its ability to offer "anything, anytime, anywhere" connectivity, thus connecting the unconnected.

This ubiquitous connectivity is expected to be the most significant impact of NTNs. A key feature is NTNs' ability to bring mobile communications to remote and under-served regions. This will help to bridge the digital divide by providing connectivity to areas lacking terrestrial infrastructure. They also play a crucial role in disaster response and emergency communications in these remote regions, enabling communication restoration in times of crisis.

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> Joaquin Torrecilla, Chief Technologist, Keysight Communications

NTNs also have the potential to overcome infrastructure challenges in developing regions, empowering communities with access to education, healthcare, and economic opportunities. By providing reliable connectivity, these networks foster social and economic development on a global scale.

Looking ahead, NTNs will continue to evolve and shape the future of mobile communications. As we move into the era of 6G and beyond, these networks will likely play an even more significant role in enabling ubiquitous connectivity and supporting emerging technologies like autonomous vehicles and the Internet of Things (IoT).

Challenges

While the future of NTNs shows great promise, the deployment of NTNs comes with its own set of challenges. Regulatory and policy considerations need to be addressed to ensure the equitable distribution of network resources and the protection of frequencies for both terrestrial and non-terrestrial networks. Environmental sustainability is another important aspect to be considered, as the proliferation of satellites raises concerns about space debris and its impact on the long-term viability of these networks.

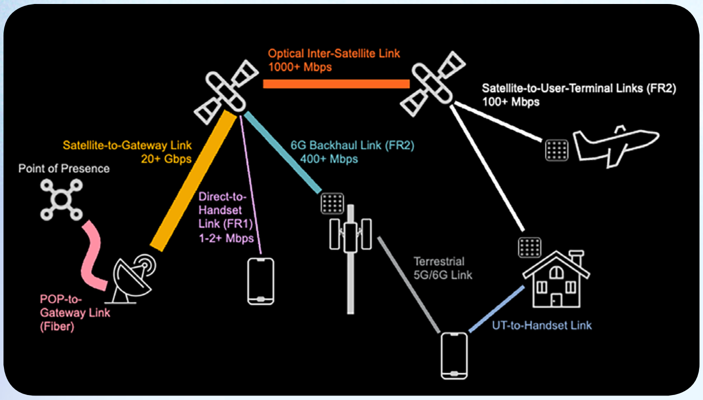
There are technical challenges as well that come with creating links with satellites and handsets. One of the main technical challenges in mobile communications with satellites is the Doppler effect, which involves the change in frequency of a wave in relation to an observer moving relative to the wave source. This means that there needs to be some compensation for the Doppler effect in the links with satellites.

The delay in sending the signal between the satellite and the handset is another factor. The delay that occurs in a GEO satellite is much different than the one that occurs in a LEO satellite.

Another factor is the recent commercial realities that have developed with massive LEO satellite constellations, like those of SpaceX's Starlink network, changing the marketplace before NTNs become fully integrated into 5G and 6G networks and leaving their commercial development and relevance in question.

NTN Architecture

Every NTN has various points of presence (POP) where the satellite network connects to the terrestrial Internet. These POPs are connected to one or more Gateways through fiber links that are in turn linked to overhead satellites with massive 20+ gigabit per second connections. These links between the Gateways and the satellites can be thought of as the wideband backhaul links that exist for terrestrial cell towers. (See figure below)



Source: Todd Humphreys, UT Austin

The satellites themselves may be linked in a mesh with their nearest neighbors in the constellation via high-bandwidth optical inter-satellite links where the data transfer speeds are around 1000+ megabits per second (Mbps). User terminals are based on low-cost phased array antennas. These may have a fixed location, such as a house, or may be attached to vehicles, such as an airplane. These satellite-to-user terminal links have speeds of 100+ Mbps.

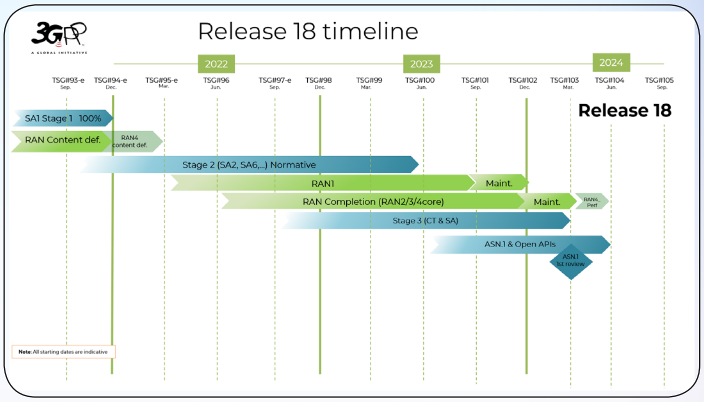
Connections with less than 50 milliseconds (ms) latency to the POP and greater than 100 Mbps throughput have already been proven. Fixed or mobile terminals can in turn deliver network access to handsets and other devices over a local wireless network.

A promising use case for broadband LEO communications is providing backhaul to cell towers in remote locations where fiber or terrestrial microwave connections are impractical. These towers can then service handsets or devices over standard cellular links. The most ambitious NTN proposals call for direct to handset links with global coverage, low latency, and rates beyond 2 Mbps.

The Role of Standardization

The 3rd Generation Partnership Project (3GPP) has established standards and targets for these NTN networks in use within both 5G and future 6G networks. These specifications are described in Release 17, which was published in 2022, and Release 18, which looks to be published in the first half of 2024.

The 3GPP is attempting to standardize all the signals and all the protocols that happen between the phone and the base station. What it doesn't take into account is what is happening in the



Source: 3GPP

satellite. There are a few key advantages of the 3GPP establishing these standards, according to industry experts.

"One of the key advantages of the standards is that with a standard you have common components, better margins for the industry and interoperability," explained Joaquin Torrecilla, Chief Technologist at Keysight Communications Solutions Group. "Another advantage is that if there's a satellite standard that is very close to the current 5G that you have in your terrestrial phone, then you can use it to send an SOS message or check your email when you are in the middle of the nowhere."

The Early LEO Massive Constellation Networks

While these 3GPP standards are aimed at making NTN operate with today's 5G and future 6G wireless networks, the visions that have led to the proliferation of low-Earth orbit (LEO) massive constellations that we see today started in the 1990s.

It's long been a goal to connect everyone on Earth using LEO satellites that could act as current base stations for our smartphones. Two big projects in the 1990s were set up around that goal. One of them being Globalstar and the other one being Iridium.

In these two examples, the satellites were well-designed and it was already clear to people at that time that they wanted to mass-produce the satellites. At the time, putting up 66 satellites in the Iridium constellation was a huge undertaking. This, of course, was before launch was as cheap as it is now. But it was an idea that came before the resources were in place to allow it to thrive. It also placed significant emphasis on the low-bandwidth direct-to-handset model.

Failure of Early Attempts

"Of course, these approaches were designed before the Internet was what it has become today," explained Todd Humphreys, professor of Aerospace Engineering at the University of Texas at Austin. "These systems were designed in the early 1990s and later were deployed in the field by the late 1990s, so it was, perhaps, forgivable that the designers didn't recognize the value of just streams of data."

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The companies deploying these networks were no doubt expecting a large user segment to emerge that hadn't existed previously and wanted access to these satellite signals everywhere and at any time, but two roadblocks stood in their way, according to Humphreys.

The first of these market roadblocks was that terrestrial mobile networks were built up more rapidly than most experts expected. Secondly, people who had had experience with these terrestrial mobile networks found the user experience of satellite mobile networks to be subpar.

"You couldn't use these systems indoors. You had to be out standing in a field for the call to go through, and then the call was sometimes dropped, and because of the high compression, we're talking only a couple of kilobits per second supported for each of the calls, it sounded like you were talking from inside a tin can," said Humphreys.

Starlink Changes the Game

In recent years, there has been a resurgence of interest in NTNs, particularly in the form of LEO satellite constellations. Companies like SpaceX have embarked on ambitious projects, such as Starlink, deploying thousands of small satellites in LEO clusters to provide global broadband connectivity.

While SpaceX's Starlink Broadband service as a LEO NTN service has emerged as a solution that realizes the early vision of Iridium, the difference between Starlink's success and the relative lack of success of Iridium comes down to timing, according to market observers.

"It's enormously expensive to field a constellation of 4200 satellites," said Humphreys. "If SpaceX is to emerge successfully from this investment—and I believe they will—it will have defied expectations, and it will be unprecedented, in the literal sense of the word."

Humphreys believes that two technologies have unlocked SpaceX's Starlink as a real game changer. One is cheap launch technology in the form of reusable rockets. The second is mass-market beamforming. Beamforming is a way of directing beams of radio signals to the right location. It's a kind of traffic-signaling system that identifies the most efficient data-delivery route to a particular user.

But it is not beamforming at the satellite, according to Humphreys, it's the beamforming at the user terminal. "Making that kind of beamforming cheap enough to offer it to the mass market has been key and that has proven to be extraordinarily revolutionary."

Recently, Amazon has also gotten into the game with its Project Kuiper LEO satellite networks that

Sixty Starlink satellites stacked together before deployment

Amazon's Kuiper antenna

offers their version of user terminals. These user terminals are reportedly even smaller than those provided by SpaceX.

“The floodgates are open now,” said Humphreys. “I think that phased arrays at low cost with high gain, high directivity are a real game changer.”

There are two scaling laws at play in the LEO satellite networks, according to Humphreys. “It scales according to the number of satellites,” he said. “There’s a linear scaling in the total throughput of the network, say the total bits per second that the network can offer collectively to the global user base.”

However, that linear scaling with the increasing number of satellites reaches a bottleneck at the number of Gateway terminals through which the satellite data eventually have to flow. The bottleneck occurs at the satellite-to-Gateway link, which is presently able to transfer data to the satellites at 20+Gbps. Current estimates are that SpaceX is utilizing fewer than 100 Gateways to send data to their 4200 satellites.

There are some challenges to simply deploying more Gateways. Establishing and maintaining these Gateways is expensive and they often have to be in rough terrain.

“The expense of plumbing these Gateways in, connecting them to a POP and then maintaining them over their life cycle may be comparable to the expense of launching the initial tranche of satellites,” said Humphreys.

While these Gateways are expensive, throughput will only scale linearly with the number of gateways. It will scale linearly with the number of satellites until the number of Gateways becomes a bottleneck, and then it will no longer scale linearly.

The satellites can talk directly to other satellites over optical inter-satellite links. Those optical

SpaceX Starlink Ground Station

inter-satellite links (OISL) can be up to one to two gigabits per second. This OISL technology along with cheap launch technology and beamforming at the user terminal has made Starlink the de facto leader in LEO communications. Without OISLs, you would need a Gateway for every satellite,

“OISL links are much more economical now than they’ve ever been, partly, it turns out, because of the mass drone market,” said Humphreys. “The sort of stabilization required in the gimbals that hold cheap cameras on drones is the very sort of stabilization required to point a laser from one satellite to another across two different orbital planes.”

Other NTN Initiatives

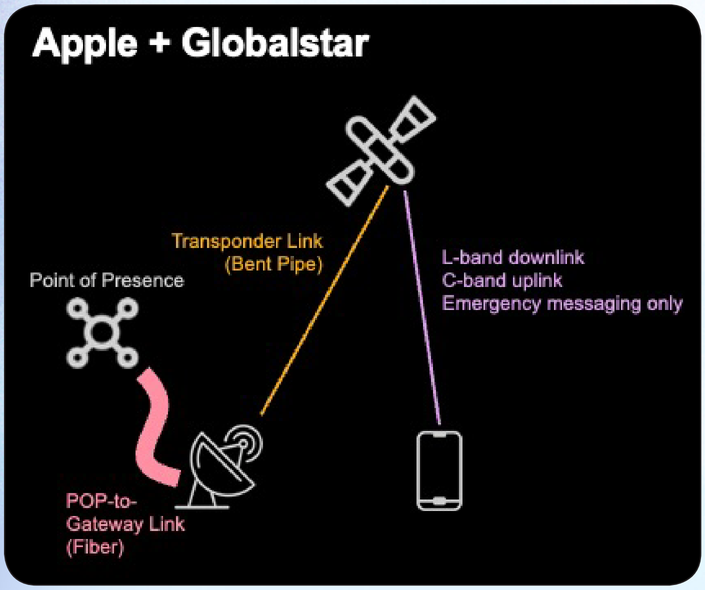
Satellite companies are launching satellites that do effectively the same thing as a 4G base station does on the ground, except that it has these modules that allow them to pre-compensate and post-compensate for Doppler effects.

Currently, none of the terrestrial mobile providers are directly working in space. They are thinking about partnerships with startup companies in space, or partnerships with well-established companies.

In addition to SpaceX's Starlink system, there are a few other notable corporate developments in the evolution of NTNs.

Apple and Globalstar

Apple has modified their phones so that they can connect with existing Globalstar satellites. The modification involved putting a special modem in them. The new satellite connections are available on iPhone 14 and iPhone 14 Pro lineups and enable emergency SOS connections via satellite. The emergency texting service could allow a user to get a text message through even if you're standing on the top of Mount Everest.



Source: Todd Humphreys, UT Austin

The network uses existing Mobile Satellite Service (MSS) spectrum owned by Globalstar. This clears up any regulatory uncertainty because the MSS spectrum is being used according to its license.

While the architecture is flexible, the partnership currently is using only 2G signals in order for Globalstar to maintain backward compatibility. This may change in the future. Globalstar did not need to change any of its hardware. However, Apple had to develop a new satcomm modem for its handsets.

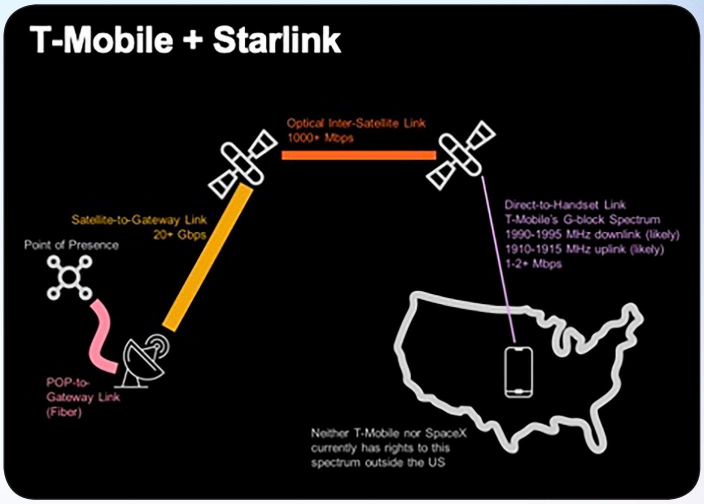
In the future, the service could potentially evolve into a global messaging service rather than merely an emergency SOS service. But it will not provide support for voice or even low-rate data without the development of an entirely new satellite constellation.

It is NTN in that it's got the network architecture of NTN: there is a transponder link up and down and it's using satellites. However, it is not within the 3GPP framework.

T-Mobile and Starlink

In August 2022, T-Mobile and Starlink announced that they were going to do a direct-to-handset mobile service. Starlink will leverage its most up-to-date satellites that have a capability to operate in the L band, which is the range of frequencies in the radio spectrum from 1 to 2 gigahertz (GHz).

T-Mobile had this L band spectrum that they inherited from the acquisition of Sprint. This is a valuable spectrum for the direct-to-handset link that operates at 1990-1995 MHz for the downlink and 1910-1915 MHz at the uplink, providing data speeds of 1 to 2 Mbps.



Source: Todd Humphreys, UT Austin

"T-Mobile didn't really know what to do with this spectrum, until they realized that it's perfect for talking with satellites because they weren't using it much terrestrially, which means that it's a quiet band," said Humphreys.

"And they're targeting 1 to 2 megabits per second directly to the smartphone. Think about this in terms of what we said earlier about Iridium's throughput. We were talking maybe 3 kilobits per second in that case. This is a thousand times more."

This spectrum can be used by existing phones and can be entirely devoted to MSS. This means there is no terrestrial interference within the US.

This was a terrestrial mobile spectrum originally when Sprint had it. As a result, there remains a bit of regulatory uncertainty whether the Federal Communications Commission (FCC) will allow this to be re-purposed as MSS spectrum. This approval seems likely, but is not guaranteed at this point.

Unlike the Apple & Globalstar initiative, this project did not require any changes to be made to the phones. This T-Mobile & Starlink initiative does not require any new standards since the phones adhere to existing 4G/5G 3GPP standards. However, it does require Starlink to design a new module for its next-generation satellites so that they can pre-compensate and post-compensate for the signals coming from the handset and the handsets will not have to be modified.

While estimates expect data speeds of 1 to 2 Mbps, it is probably more realistic that 1+ Mbps data speeds will only be achievable outdoors. Nonetheless, when one considers that Iridium's service is only able to achieve 3 kilobits per second ,1 to 2 Mbps directly to the smartphone looks to be a major upgrade.

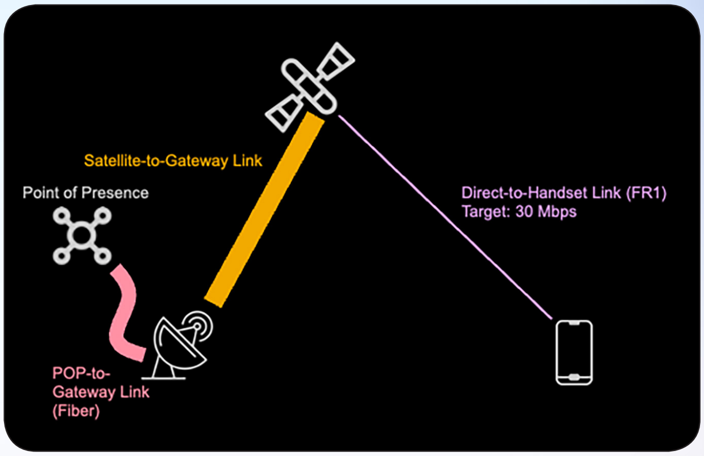
The other big issue is that T-Mobile won't be able to use this spectrum outside of the US. These frequencies are only owned by T-Mobile in the US. T-Mobile is trying to convince the rest of the world that they should dedicate some of their spectrum just for direct-to-satellite links. But this will likely be a hard sell since giving up your valuable spectrum for an unknow market doesn't currently make business sense.

AST SpaceMobile

There is an entirely new player in the market that is looking to change the game. Texas-based AST SpaceMobile is aiming to achieve a direct-to-handset link of up to 30 Mbps. Like the other NTN initiatives, they are aiming to have their system work with unmodified handsets so they need only adhere to current 3GPP standards and not those outlined in Releases 17 and 18.

Back in September 2022, AST SpaceMobile launched its massive BlueWalker 3 satellite into orbit. In April 2023, it announced the successful completion of the first-ever two-way voice calls, directly to everyday unmodified smartphones using the BlueWalker 3 satellite. The company did not report whether they had achieved their proposed 30 Mbps data speeds, but there was a connection.

The plan for AST SpaceMobile is to partner with various mobile operators, using the operators'



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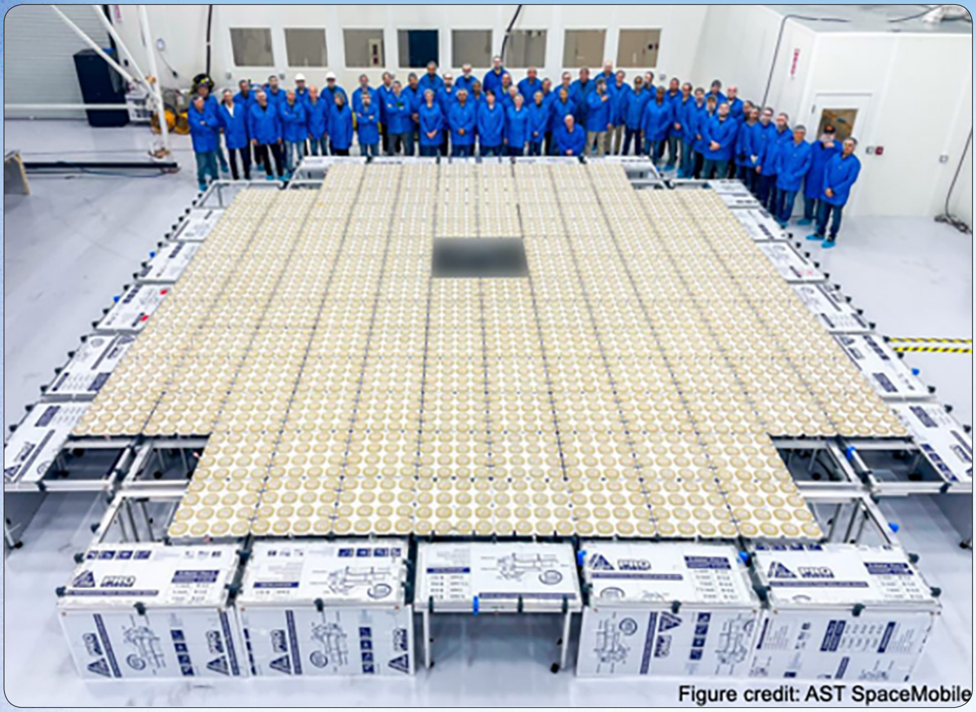

Figure credit: AST SpaceMobile

spectrum. It will be key that this spectrum is devoted entirely to MSS spectrum or else there will be terrestrial interference, except in unpopulated areas. This again raises regulatory questions and whether the FCC will allow terrestrial spectrum to be re-purposed for MSS spectrum.

The antenna is huge (see photo). It is what is known as a phased-array antenna, which is a computer-controlled antenna that creates a beam of radio waves that can be electronically steered to point in different directions without moving the antenna. In these types of antennas, you have to maintain what's called phase coherence across this array. In other words, all of elements of the antenna have to be working in unison such that every wave they generate ends up being coherent at the location of the user terminal.

The antenna is also a flexible structure that requires the flexure to be monitored. Because the strategy of the AST SpaceMobile is to work with different providers and their unique spectrums, the antenna needs to compensate for the fact that you might be working at different frequencies.

AST Mobile does not have its own frequencies. Instead, they have to partner with a terrestrial provider who allows them to broadcast in that terrestrial provider's frequencies.

"Any time you're dealing with even a single frequency and a phased array of this size, it becomes challenging to maintain the phase coherence across the array," explained Humphreys. "Imagine if you're having to hop between frequencies. Maybe you barely get it to work for a particular band and then you're flying over Africa and your terrestrial partner in Africa has a different frequency. You have to pop over to that band."

While Humphreys concedes there's a fair degree of technical risk in this approach, he believes that an ambitious approach like AST SpaceMobile's is necessary to move the technology and markets of NTNs forward.

Bringing NTN Back to the 3GPP Standard

None of these NTN initiatives described above is dependent on the 3GPP standards body thus far. Nonetheless, what's driving 3GPP specifications for NTNs is establishing direct connections with both the user handset and Internet of Things (IoT) devices.

"If you don't have the implementation of the 3GPP NTNs standard in the phone and legacy phones, then you have to handle all the complexity in the base station or in the satellite. And that requires lots of tricks," said Keysight's Torrecilla.

While these tricks might provide limited connectivity good enough for some SOS messages, and, eventually, could even be good enough for reasonably good phone call, it seems it comes at the expense of lots of proprietary algorithms and circuitry in the satellite, according to Torrecilla.

Torrecilla argues that the current emphasis put on making current phones work with proprietary satellite constellations may not make sense when you take into account that people change phones every three or four years.

"This means in four years most of the phones in use will be able to support the NTNs standard, so why would you deploy something proprietary, more expensive, on thousands of satellites for something that eventually, in three or four years, most of the people will have supported by the standardized system," questioned Torrecilla.

Torrecilla has witnessed momentum grow for incorporating NTN into 5G and 6G networks since 2021 when Keysight started its own NTN testbed. This momentum became even more pronounced last year when Release 17 standard was officially published.

"Two years ago, there were just a few companies pushing hard for NTN, but then it got lots of momentum," said Torrecilla. "Now, I would say NTN is one of the most supported work items and study items in 3GPP. There's lots of support and there's lots of companies that traditionally have not been part of 3GPP that joined 3GPP because of it."

As evidence of this momentum, Keysight in partnership with Samsung demonstrated at 2023 Mobile World Congress this year SMS two-way texting over a live 5G NTN connection with a Samsung Electronics System LSI mobile modem platform.

This demonstration was also a demonstration of how Keysight has been supporting the NTN mobile networks from development to final products for years.

"Our instruments can be used from the early development phase to test subsystems of the final device to the final testing once you have the device completely integrated and you want to test that," said Torrecilla.