MediaTek 6G Technology White Paper

Satellite and Terrestrial Network Convergence

White Paper

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Executive Summary

MediaTek believes that integrating satellite and terrestrial mobile networks to offer pervasive connectivity across the world will not only enable a new era of innovative digital services, but also significantly contribute to the United Nations Sustainable Development Goals. Compared with proprietary satellite communication technologies, 6G non-terrestrial network (NTN) technology based on a 3GPP open standard can leverage the economies of scale from the existing global mobile cellular ecosystem to bring satellite communication from a niche market to mainstream consumer and business markets leveraging common devices that switch between satellite and cellular networks for an always connected user experience. Compared with 5G NTN technology which was added at a later release, 6G NTN shall be natively considered from the beginning of the 6G physical/protocol layer design stage. This would allow joint optimization of technologies for terrestrial networks and non terrestrial networks.

MediaTek's research has identified four major new technology areas for 6G that can further enhance NTN: efficient waveform design, enhanced mobility, massive satellite beamforming and cellular/satellite spectrum sharing. High level concepts and initial research results are provided in this white paper. More detailed system design and evaluation results will follow in future white papers.

1. Introduction

With 5G NTN specified in 3rd Generation Partnership Project (3GPP) Release 17 for NR/IoT, and further specification in Release 18, together with trials and deployment of these standardized solutions, this publication aims at providing a timely outline for the next generation, global 6G NTN standard.

As the proponent of 3GPP NTN standardization since 3GPP Release 17, MediaTek has taken a leading role in the system design, standardization and ongoing evolution of 5G NTN, both for NR NTN and IoT NTN. This includes the world's 1st 5G IoT NTN and NR NTN PoC, and commercialization experience with economies of scale leveraging MediaTek terrestrial NR devices and IoT devices. With this experience in hand, MediaTek holds a central position to define and drive the vision and realization of next generation 6G NTN.

3GPP NR NTN and IoT NTN standards were designed and built on the terrestrial NR and IoT specifications, re-using as much as possible to meet the new requirements of NTN and enable new growth opportunities for NTN markets. However, Release 17 and on-going Release 18 3GPP NTN specifications do not support a seamless user experience from terrestrial to NTN. Users' experience will likely be compromised due to the relative scarcity of satellite spectrum in the low frequency band (i.e., sub-6 GHz) and in the upper mid frequency bands (i.e., above 10 GHz frequency).

With the likely adoption of open RAN architecture in NTN deployments, there is an opportunity to bring more flexibility and intelligence with machine learning to enable integration of TN and NTN. The adoption of 3GPP NTN standards and deployment will set the scene for a once-in-a-generation transformation of mobile networks with ubiquitous coverage to support mobile broadband services anywhere any time. This would enable a fundamental transformation to mobile networks and pave the way towards achieving the United Nations Sustainable Development Goals, which aim at significantly increasing access to Information and Communications Technology (ICT) and strive to provide universal and affordable access to the Internet in the least developed countries [1]. The United Nations Sustainable Development Goals are a set of 17 critical goals for sustainable development to improve Human lives whilst preserving nature and its biodiversity (No poverty; Zero hunger; Good health and well-being; Quality education; Gender equality; Clean water and sanitation; Affordable and clean energy; Decent work and economic growth; Industry, innovation and infrastructure; Reduced inequalities; Sustainable cities and communities; Responsible consumption and production; Climate action; Life below water; Life on land; Peace, justice and strong instituation; Partnerships for the goals).

Mobile wireless communication systems allow the exchange of information at a distance, with limited footprint on the natural ecosystem compared to wireline solutions and allow reaching into areas otherwise difficult to access. Satellite systems bring this one step further, reaching where traditional mobile communications systems cannot. The tight integration of both systems leverages the economies of scale of mobile systems, the reach of satellites and the power of wireless communications to deliver a truly unique offering that can allow the exchange of information anywhere and anytime on Earth. Such unprecedented technology, spearheaded in 5G and central to 6G will help contributing to achieving the above goals. By virtue of a few simple examples, we illustrate below how this could be achieved. Making such integrated NTN/TN technology available will foster further innovation that we expect will strengthen humans'response to United Nations Sustainable Development Goals.

Of the many causes of inequalities, access (or lack thereof) to information is a fundamental one. The provision of an affordable ubiquitous medium that can provide access to information e.g. for education, for health will have a transformative effect to reduce inequalities worldwide, especially in communities that today are disconnected due e.g. to simply living in remote areas. By allowing deployment of IoT NTN sensors in remote and inaccessible areas, water sources can be monitored with virtually no impact on the natural ecosystem itself whilst contributing to helping the lives of 3 billion people for whom the quality of the water is, today, unknown. Fire monitoring sensors can be deployed in areas prone to forest fires thus allowing a much faster response that can help protect forests, their wildlife and the people in their vicinity, while also preventing forest-fire-induced carbon emissions. Similarly misc. other IoT NTN sensors could be used for helping detect illegal deforestation and logging, poaching etc.

6G NTN will help address the issue of satellite spectrum scarcity beyond 5G and its evolution, with one global standardized technology, by allowing flexible and complementary sharing of spectrum across terrestrial networks and NTN.

Our vision for 6G NTN is an integral part of 6G System that will be highly scalable, addressing any deployment scenario in the leanest possible way. The 6G System will consist of integrated and super-heterogeneous wireless communication systems, delivering pervasive mobile connectivity in a truly ubiquitous manner for anything and everything between short-range and satellite communications. The revolutionary advances in artificial intelligence and machine learning will play a central role in making this 6G vision a reality; setting up, operating and managing such a system will require novel tools that can automatically and dynamically tailor its overall configuration and operation to the requirements at hand, without human intervention, while iteratively learning to improve its performance.

6G NTN will deliver mobile broadband with high capacity and high data rates for smartphones and IoT devices, outclassing current 3GPP NTN systems. Our vision for 6G NTN will maximize convergence and spectrum sharing between terrestrial 6G and NTN devices, to fully leverage economies of scale.

Key drivers and enablers such as waveform design, mobility enhancements, and interference mitigation that will be of high importance for 6G NTN will be detailed in this white paper.

2. Satellite and Terrestrial Network Convergence Trends

Compared with traditional satellite communication systems, the recent advancement by 3GPP NTN technology [2] aimed at enhancing terrestrial 5G mobile technology (radio and core) to support satellite communications, offers a disruptive solution poised to transform both satellite and terrestrial cellular ecosystems. On one hand, satellite operators can leverage the existing 5G mobile technology ecosystem and its economies of scale to bring satellite communication into the mainstream. On the other hand, terrestrial mobile network operators can leverage the coverage advantage of satellites to provide service in areas that would otherwise be out of their reach, and thus not only broaden service coverage to existing customers but also allow them to serve new types of customer. The tight integration of satellite and terrestrial mobile technologies within a common system at both radio access and core opens up a new frontier that no other technology can reach. With the fundamental design requirement to allow operating both terrestrial network and satellite connectivity in a single multi-mode device [3] which could flexibly switch between terrestrial and satellite networks, 3GPP NTN technology is now turning terrestrial mobile and satellite ecosystems from competition to partnership (e.g., complement service coverage, traffic roaming based, retail channels including smartphone retail). Satellite and terrestrial convergence will be a major trend from 5G toward 6G. The following sections will further investigate the potential use cases and advantages.

2.1 Smartphone Direct Access to Satellite

Early mobile phones with external antenna evolved to an integrated design in smart phones. Satellite operators and consumers alike will likewise benefit from satellite communications enabled on consumer-grade smartphones i.e., with no bulky protruding antenna, see Figure 1. A series of annoucements issued in 2022 demonstrate a growing momentum to bring such solutions to the market.

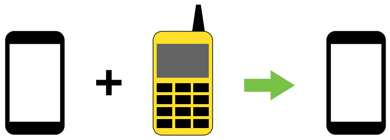

Figure 1. Integrating terrestrial and satellite communications into a single device

These solutions can be classified into four different technical options, as shown on Figure 2:

- **Option #1** consists in integrating legacy satellite communication solutions into new 5G smartphones. This option has the drawback of using legacy technologies that are not based on global standards and are not harmonized with terrestrial technologies – both aspects are crucial to drive economies of scale in the device. Because the legacy Low Earth Orbit (LEO) satellites have limited capability (e.g., equivalent isotropic radiated power (EIRP), antenna gain-to-noise-temperature (G/T)) and are unable to make up for the link budget loss caused by replacing bulky antennas with regular smartphone antennas, the achievable data rates will be generally low and only suitable for messaging services (e.g., emergency use). The scarcity of satellite spectrum in the sub-6 GHz frequency band and the Signal-to-Noise Ratios (SNR) experienced at the satellite receiver and the device receiver limit the achievable data rates. In upper mid frequency band above 10 GHz, where there is more spectrum available for satellite, an external dish or array is needed to achieve high SNR at the device and the satellite with high data rates experience.

- **Option #2:** relies on proprietary satellite onboarded Long Term Evolution (LTE) base station, i.e., base station technology implementation to compensate for the latency, Doppler and link budget limitations. Due to various LTE device capability restrictions (e.g., 10ms scheduling delay tolerance, maximum Doppler tolerance in high-speed train scenarios), the interoperability testing (IOT) could be quite challenging in the field, because legacy LTE device implementation did not assume the base station signal may come from LEO satellites instead of terrestrial base stations.

- **Option #3** makes use of the 3GPP IoT NTN technology implementation on smartphones for satellite services (e.g., messaging, small data). According to previous field experiments [4], new 5G satellite Narrow-Band Internet of Things (NB-IoT) technology establishing a bi-directional link of several kbps from MediaTek's satellite-enabled standard NB-IoT devices to a commercial Geosynchronous Equatorial Orbit (GEO) satellite would be feasible, thanks to sophisticated radio technologies designed for cellular IoT. By leveraging the global coverage strength of the GEO satellite technology, the vision of "always-connected" smartphones was recently realized for satellite messaging systems with Satellite

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Bullitt connect service [5], [6].

- **Option #4** makes use of the 3GPP NR NTN technology on smartphones for wideband satellite services (e.g., voice call, satellite data services). Although NR NTN can support wider signal bandwidth compared to NB-IoT NTN, the experiment observes that more advanced LEO satellite capabilities (e.g., EIRP, G/T) are essential to close the link budget gap and offer Mbps level data rates. This option promises to be the long-term trend, enabling future 5G smartphones to directly connect with LEO satellites [7].

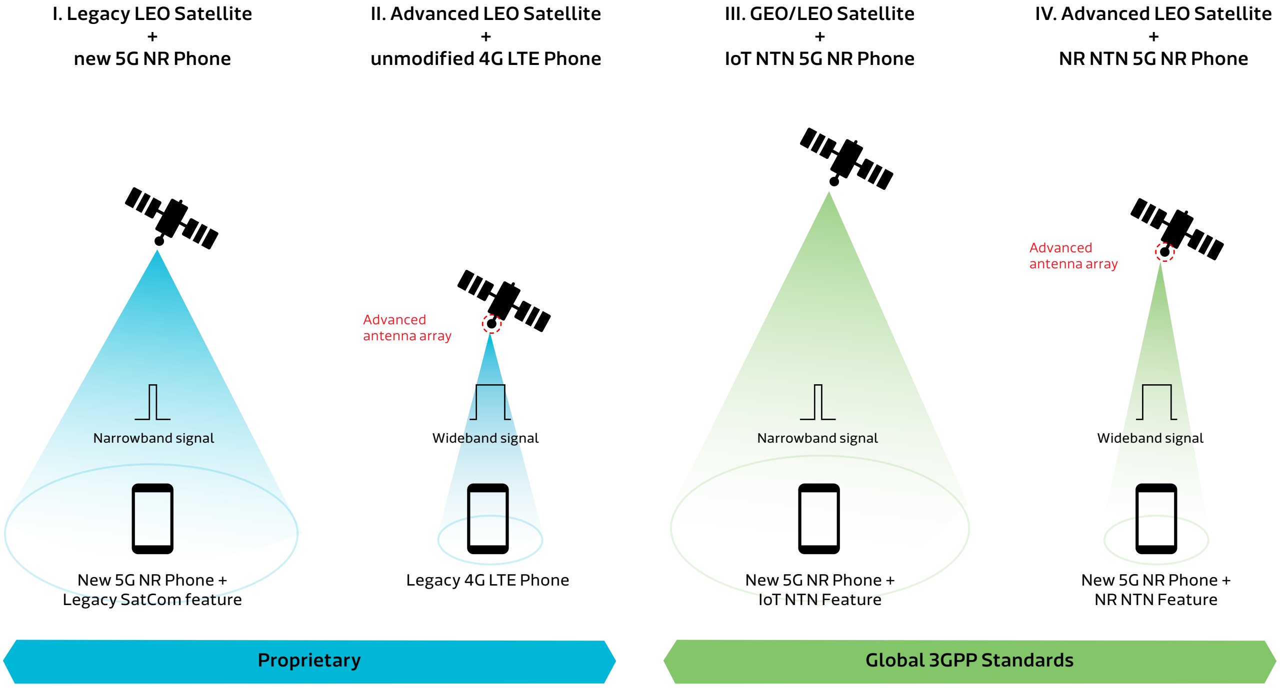

Figure 2. Technology Options for direct Smartphone access to Satellite

2.2 Automotive Access to Satellite

The early reports reflect an increasing requirement for data connectivity in automotive markets [8]. Connected vehicles already support 4G-enabled mobile services and infotainment. Connected Vehicle Cloud Services with always connected, software-defined, vehicles to enable more services such as telematics, infotainment, navigation, and fleet management is an increasing trend to provide safe, reliable and engaging mobility that will benefit from ubiquitious coverage provided by satellites. The release of 5G V2V/V2X standard will benefit autonomous vehicle development at Levels of automation 3, 4 and eventually 5, increasing the safety of public roads. However, this is not only about the connectivity for the vehicle market itself, but also for creating opportunities in adjacent markets such as EV charger stations [9], which may be located in remote areas without terrestrial mobile coverage. This requirement defines multiple levels of data bandwidth from satellite communications. Research has projected the market for global satellite communications will increase from USD 77.1 billion in 2022 to USD 159.6 billion in 2030 [10]. A vehicle firmware update is typically done using WiFi while car is parked, or on the move using a cellular connection [11], [12], however if there is a critical fix in relation to safety or security, in future this could be sent via satellite communications. Autonomous driving systems are high complexity as they require a high-level of technology integration such as sensing, localization, perception, decision making, as well as reliable interactions with cloud platforms for traffic information, high-definition (HD) mapping/routing, and data storage. Edge computing systems are essential for autonomous driving to minimize the latency to process incoming sensor and communications data. This still requires a cellular connection and should be complemented by satellite communications when the vehicle is not in range of terrestrial networks. Connected driveless cars require low latency and increasing data rates as the level of functionalities grow (Level 3, to 4, to 5). Satellite communications will play an important role in connected vehicles of the future in a complementary way with terrestrial networks.

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2.3 Fixed Wireless Access and IoT Access to Satellite

IoT access to satellite can complement fixed wireless access for some critical applications (e.g., IoT, key distribution) which require low latency across long communication distances. The inventory check and payments from vending machines in remote areas require a payment system using low data-rates, which is an ideal use-case for NTN communication.

Among other MediaTek research [13], we evaluated that satellite IoT can be used for early wildefire detection, which could largely mitigate the carbon emission for the sustainability objective. The core concept is to deploy extensive off-grid fire detection sensors with satellite IoT connectivity across remote areas with high wildefire risk. Compared with traditional fire detection methods (like watchtowers or cameras), the analysis shows that a reduction of over 90% of the burning area could be achieved, based on the California fire database. It could also save 90% carbon emission (using the same California wildefire reference) with over 10 billion USD saving, assuming a CO2 emission cost of 10 USD/tons. These research results show how NTN technology could significantly contribute to UN SDGs and should be included as 6G system design requirements from the outset.

2.4 3GPP NTN Standardization

Three types of satellite service links are supported in 3GPP standards as illustrated in Figure 3 allowing the support of any type of orbit whether geo-stationary, low- or medium-Earth orbit.

- **Earth-fixed:** provisioned by beam(s) continuously covering the same geographical areas all the time.
- **Quasi-Earth-fixed:** provisioned by beam(s) covering one geographic area for a limited period and a different geographic area during another period.
- **Earth-moving:** provisioned by beam(s) whose coverage area slides over the Earth surface.

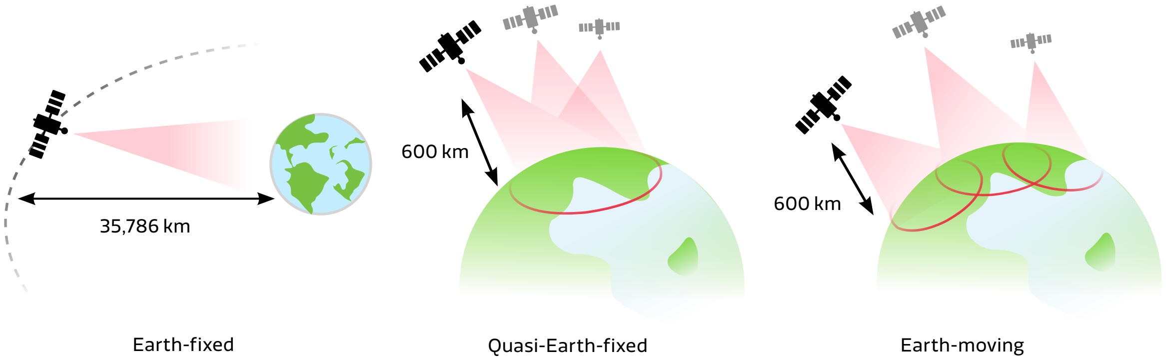

Figure 3: Service link types

3GPP NTN solutions are tightly integrated with existing terrestrial solutions (hereafter referred to as TN i.e., “Terrestrial Network”). The transparent mode NTN architecture relies on a traditional 3GPP terrestrial mobile network comprising both access and core networks where the ground stations (gateways) provide the connectivity bridge between the terrestrial access network and the orbiting satellites. The connections between gateways and satellites are called feeder links, while the connections between satellites and mobile devices are called “Uu” service links. The satellites repeat[1] the Uu radio signals between the feeder link and the service link, as shown on Figure 4. Through necessary satellite, network and device adaptation, this approach allows virtually any NB-IoT, LTE Machine Type Communication (LTE-M) or NR solution to provide a satellite service.

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[1] Conformant to “transparent/bent-pipe” i.e., frequency translation approach. The “regenerative” (i.e., onboard base station) architecture is not currently supported in 3GPP specifications.

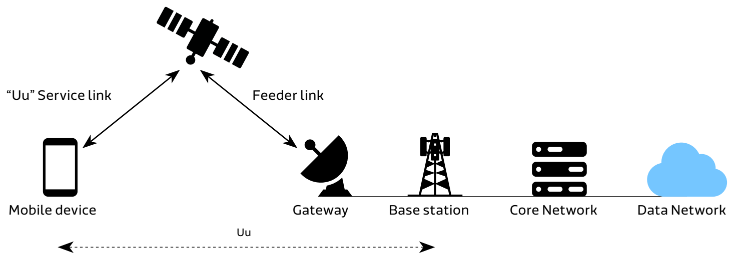

Figure 4. 3GPP NTN architecture – transparent mode

The main challenges of integrating NTN communications into TN are primarily caused by the extreme distance to and/or velocity of the satellite. Specifically:

- Timing, Doppler shift
- Mobility (especially in case of non-geostationary satellites)
- Link budget (not using a bulky antenna)

In a TN, the maximum 2-way transmission delay (i.e., round trip time, RTT) between a device and a base station is in the order of 666 μs for a maximum cell radius of 100 km. However, depending on the satellite deployment, the delay can range between several ms to 100 ms. This results in a misalignement of the downlink (DL) timing at the device side and of the uplink (UL) subframe timing at the base station side. To solve the ambiguity of misaligned timing at the device and the base station, the DL timing and UL timing are frame-aligned at the uplink time synchronization Reference Point. The reference point is configurable and can be set at the satellite, at the base station or at a certain point on the feeder link. The timing relationships for scheduling of UL physical channels are adjusted by the network according to the Reference Point. NTN transmissions can also be subject to major Doppler shifts of several 10s of kHz depending on the satellite orbit. The device calculates and pre-compensates for the satellite propagation delays and Doppler shift using its own Global Navigation Satellite System (GNSS) location and the satellite ephemeris broadcast on System Information Block (SIB) before transmitting on the uplink. The satellite ephemeris is valid at a reference time for UL synchronization denoted by the Epoch time.

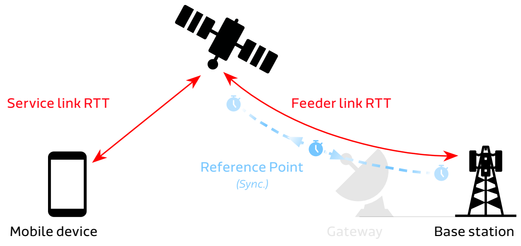

Figure 5: Service link RTT, Feeder link RTT, and Reference Point for DL-UL timing alignment

The 3GPP Release 16 study phase included a link budget analysis at different satellite orbits using parameters typical in satellite industry such as frequency bands, Effective Isotropic Radiated Power (EIRP), figure of merit G/T, beam diameters, path loss, and so on. Devices for handheld and with a Very Small Aperture Terminal (VSAT) were considered in the analysis. It was shown that the link budget can be closed in the uplink and downlink in most satellite scenarios with some compromise, for example with a smaller bandwidth used for uplink transmission. 3GPP Release 18 is currently looking at coverage enhancements for handheld device in the sub-6 GHz band with additional antenna gain losses in the device. The combination of path loss due to the long propagation distance and antenna gain loss in the device results in low SNR on both DL and UL directions. One solution is to increase the transmission power either in the device or in the satellite. Using legacy waveform design in 3GPP NTN, peak-to-average power ratio (PAPR) and out-of-band (OOB) power leakage make this solution inefficient and with increased complexity.

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3GPP NTN is defined under the principle of Earth-fixed tracking areas[2] regardless of the type of deployment (i.e., GSO or NGSO). This principle considerably simplifies the integration of NTN in the core network, which remains on the ground. The definition of tracking areas is related to the topology of the core network and of the access network on the ground. Depending on the network topology, a satellite cell could effectively span across multiple tracking areas. All tracking areas served by a given satellite can be indicated to devices in the satellite cell. The main impact on the device side is its ability to receive and handle multiple tracking area identifiers in a given cell – in principle however, its behavior in terms of mobility management remains unchanged. It is the responsibility of the network on the ground to route core network signaling appropriately between the device and the core network.

In terms of radio mobility, Idle mode measurements and connected mode measurements are used for cell reselection and handover, respectively. As an option, the device location and a reference point in the beam footprint broadcast on SIB can be used to trigger devices measurements closer to the beam boundary based on a configured threshold. Time-assisted cell reselection can also be used for quasi Earth-fixed cell to indicate the time when a cell stops covering the current area.

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[2] Tracking area: an area of the network that consists of one or more (radio) cells. A cell broadcasts the tracking area to which it belongs. The network knowing a registered device has entered and not left a given set of tracking areas (aka tracking area list or registration area of the device) does not need to page the device in the entire network to reach the device, but only in this set. A device that detects a cell does not belong to any tracking area in its tracking area list/ registration area notifies the network so the network can update its tracking of the device.

3. 5G Non Terrestrial Network (NTN) Technology Trial Observations

3.1 IoT NTN Technology Trial

The IoT NTN trial, as shown in Figure 6, demonstrated NB-IoT viability for Satellite in a bi-directional link successfully established in August 19th , 2020 [4], [14]. Table 1 summarizes the set-up parameters used in this trial, where the device and base station were 525 km apart:

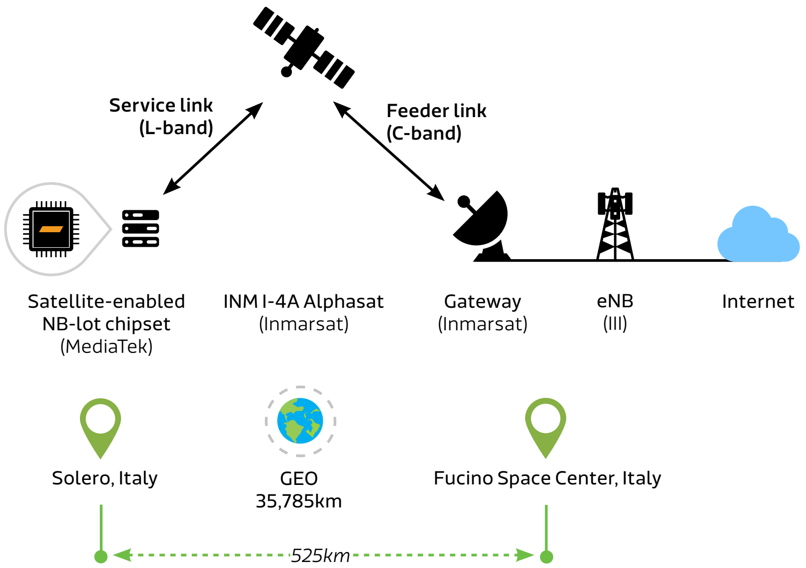

Figure 6: IoT NTN trial setup

Device: MediaTek satellite-enabled NB-IoT chipset	Base station: Institute for Information Industry (III)
• Power Class PC3 (23dBm) • Linearly polarized antenna (-3dB polarization loss) • Tx / Rx antenna gain: 0 dBi	• Local connection to Satellite Gateway via proprietary interface • Internet connection
Satellite: Inmarsat INM I-4A F4 Alphasat (EMEA) -band, GEO orbit • User / Service link with circular polarisation on L band, elevation angle 40° • Transparent payload	

Table 1 Set up parameters for the IoT NTN trial

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The real-time trial successfully demonstrated initial cell access (RACH[3], RAR[4], CR[5]) and bi-directional data transfer. The link budget was closed on UL and DL with the following Rel-14 NB-IoT functionality tested:

- Cyclic Prefix – Orthogonal Frequency Division Multiplexing (CP-OFDM) on forward link with DL physical channels Narrowband Primary Synchronization Signal (NPSS)/ Narrowband Secondary Synchronization Signal NSSS,Physical Downlink Shared Channel (PDSCH), Physical Downlink Control Channel (PDCCH) and reverse links with UL physical channels Physical Random Access Channel (PRACH), Physical Uplink Shared Channel (PUSCH) (Single Tone)
- Moderate repetitions on DL and UL with data rates of several kbps sufficient for conversational text messages.

The tested functionality also included UL scheduling and Medium Access Control (MAC) timers with full Timing Advance (TA) including access link Round Trip Delay (RTD) and feeder link RTD. The maximum full TA in cell was used for message 3 (i.e. first UL transmission scheduled by RAR, e.g. RRC connection request) scheduling delay and Hybrid Automatic Repeat Request (HARQ) scheduling delay. The MAC timers on RAR window offset and CR timer offset were extended by device-autonomous full TA

The UE transmission met specified legacy UL synchronization requirements by means of device pre-compensation using real-time satellite assisted system information and GNSS-acquired device location. Projections were used for real-time satellite position and velocity in device and base station. The device pre-compensation of satellite delay and frequency offset before UL transmission were demonstrated with the satellite delay and frequency offset predicted from real-time satellite position and velocity via simple on-device processing.

The early adoption of IoT NTN has started, with commercial use in smartphones and battery-powered dongles, as shown in Figure 7.

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Figure 7: IoT NTN on smartphone and dongle

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[3] Random Access Channel
[4] Random Access Response
[5] Contention Resolution

3.2 NR NTN Technology Trial

The NR NTN lab trial [March 2023], with setup as shown in Figure 7, has allowed the involved parties to evaluate the NR NTN performance according to the 3GPP Set 1 LEO 600 Km parameters in [7].

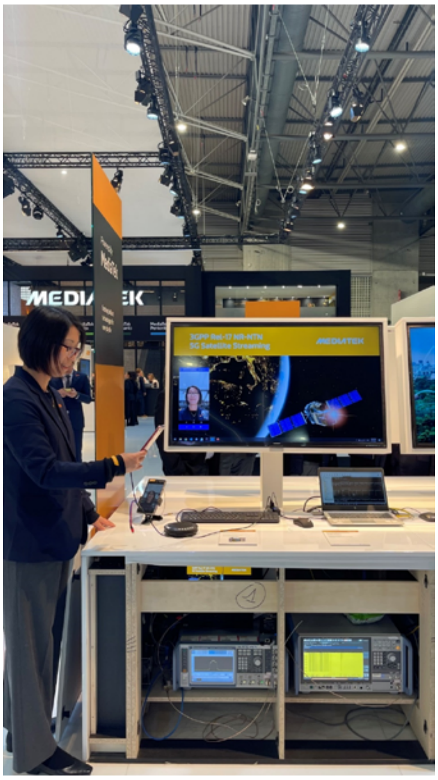

Figure 8: NR NTN conductive trial setup

The important configurations used in the trial are listed below:

Parameters	**Value**
Satellite trajectory	LEO 600 Km
Link budget parameters	Set 1 [3]
Frequency	S-Band
Bandwidth	5 MHz
UL Resource Block (RB) allocation	3 RBs (540KHz)
DL SNR range	8 to 13 dB
UL SNR range	5 to 10 dB
DL antenna configuration (Satellite to device)	1Tx by 2Rx
UL antenna configuration (device to Satellite)	1Tx by 1Rx
Satellite elevation during a flyby	36° → 90° → 36°

The throughput behaviour over several satellite flybys are shown in Figure 8. The DL throughput observed was between 5.5 Mbps and 7 Mbps, while the UL throughput was between 0.3 Mbps and 0.5 Mbps. The dips in throughput between 2 successive flybys are due to the sudden change in channel Doppler between the start and the end of the satellite flyby.

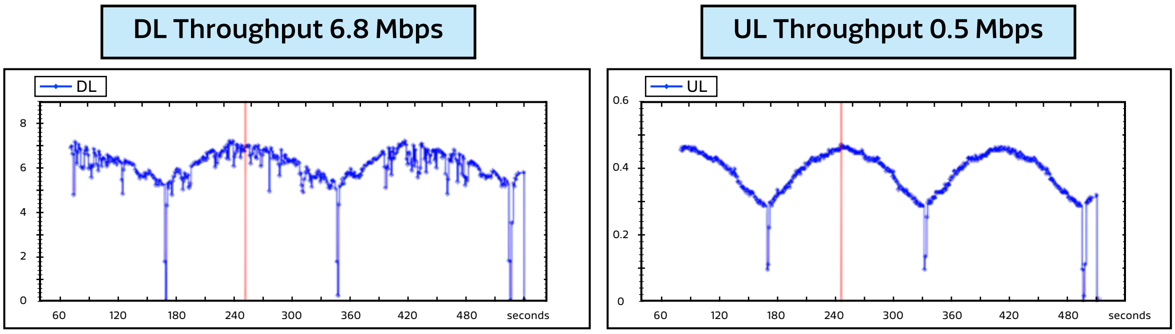

Figure 9: Throughput evaluation during satellite flyby

This same test setup was used for voice over Internet Protocol (IP) and video calls over internet from a NTN device to a TN device, as described by Figure 9. The tests have shown that the NTN link allowed for a high quality voice call and a reasonable quality video call, while the radio link failure between flybys had a minor impact on the experienced link quality.

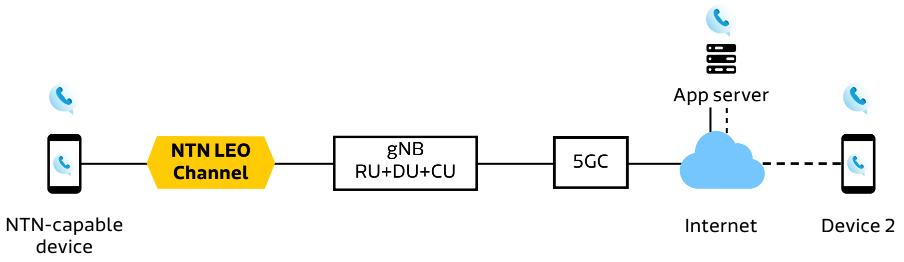

Figure 10: Configuration of IP voice and video calls over internet

3.3 Link Budget Analysis and Areas to Enhance

The link budget is a cornerstone metric for all communication systems. NTN communication is categorized into two main operations in bandwidth based on its physical limitation. Two sets of satellites are defined based on their orbital operation: legacy Geostationary satellites (GEO) and new Low/Medium Earth Orbit (LEO/MEO) satellites. The distance between the satellites and ground stations limits the received signal strength due to the Radio Frequency (RF) fading model. Therefore, GEO satellites are natively suitable for low data rate communications with high latency in the order of 100s of ms and wider coverage areas. On the contrary, LEO/MEO allow for larger data rates and lower latency in the order of 10s of ms over narrower coverage areas from each satellite.

This study focuses on the LEO/MEO satellite-based communication, which we expect will be the baseline for 6G NTN deployments. Paired with the advancement of frontend and antenna technologies, both ground/terminals and satellites can achieve a better link budget with phased array technologies. One can further categorize the satellite into bent pipe and regenerative architectures, where the bent pipe only redirects the signal to the ground stations using NR protocols, while regenerative satellites have fully functional base stations operational onboard. These two architectures lead to different link budget requirements.

Table 2 shows the link-level budget for LEO satellite systems in Ka-band based on a study phase in 3GPP Release 16, as captured in Set-1 satellite parameters in TR 38.821. The study assumed a VSAT in the device with 400 MHz in the Ka band. The link budget with the VSAT in the device provides moderate DL and UL SNR. Alternatively, a phase array antenna could replace the VSAT in the device, leading to larger beamforming gains and a smaller satellite beam footprint.

Such anetanna configurations could be used with some compromise for the achievable data rates and target SNR for the DL and UL. As a baseline, 6G NTN should at least assume LEO satellite system parameters providing link budgets similar to the 3GPP Set-1 satellite parameters.

Satellite orbit		LEO-1200	LEO-600
Satellite altitude		1200 km	600 km
Satellite antenna pattern		Section 6.4.1 in [3]	Section 6.4.1 in [3]
Equivalent satellite antenna aperture	Ka-band (i.e., 20 GHz for DL)	0.5 m	0.5 m
Satellite EIRP density		10 dBW/MHz	4 dBW/MHz
Satellite Tx max Gain		38.5 dBi	38.5 dBi
3 dB beamwidth		1.7647 degrees	1.7647 degrees
Satellite beam diameter		40 km	20 km
DL SNR		9.1 dB	8.5 dB
Equivalent satellite antenna aperture	Ka-band (i.e., 30 GHz for UL)	0.33 m	0.33 m
G/T		13 dB K^{-1}	13 dB K^{-1}
Satellite RX max Gain		38.5 dBi	38.5 dBi
UL SNR		13 dB	18.4 dB

Table 2 Link-level budget for LEO satellites in Ka bands.

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4. 6G NTN Technology Directions

Increasing user data rates, minimising latency, and maximizing the user capacity will be major goals for future 6G satellite connectivity. Operating over wider spectrum bands would lead to larger data throughput in the order of tens of Mbps in good SNR conditions on the downlink and uplink, which is an order of magnitude greater than 5G NR NTN solutions for smartphone scenarios. This will enable data-hungry applications such as video streaming or video calls via satellite communications. Low latency may be achieved by increasing the size of packets that can be transmitted per subframe with higher reliability, which will significantly improve the user experience of real time applications such as gaming, and remote operation. Capacity could be increased by at least an order of magnitude compared to 5G NR NTN, allowing it to support a larger number of simultaneous user calls with advanced multiplexing capability in time, frequency, and space dimensions. Improvements in the design of modem and RF front-end components for a better link budget will be needed to achieve these 6G NTN gains. In order to support improvements in these Key Performance Indicators (KPIs) for the 6G satellite access, several novel features are introduced in this section.

4.1 Efficient Waveform and Transmission Techniques for Coverage Enhancements

Coverage enhancement for smartphones to support NTN in LEO scenarios are currently within the scope of 3GPP 5G NR NTN Release 18 work. The combination of path loss due to the long propagation distance and antenna loss in the device results in low SNR on both DL and UL directions. One solution is to increase the transmission power either in the device or in the satellite. Using Cyclic Prefix-Orthogonal Frequency Division Multiplexing (CP-OFDM) in 3GPP NTN, high Peak-to-Average Power Ratio (PAPR) and Out of Band (OOB) power leakage make this solution inefficient and with increased complexity. Another drawback is that the high PAPR and OOB will make it more challenging to coexist or enable spectrum sharing between LEO and other systems.

To avoid inter-symbol interference (ISI), a rectangular pulse shape is adopted in 5G NR. The corresponding signal in the frequency domain is a Sinc function, whose sidelobe drops slowly and causes OOB power leakage. However, synchronization between devices operating in different systems may not be feasible. Spectrum sharing across multiple systems that are not synchronized would result in high level of interference from OOB power leakage of the rectangular pulse and lower spectrum efficiency. Furthermore, the maximum transmission power would need to be reduced to prevent unacceptable leakage interference to the nearby band, which is detrimental to enhancing the coverage area in a LEO scenario.

The high PAPR of CP-OFDM signal significantly reduces a power amplifier's efficiency. This is a known drawback of CP-OFDM. To reduce PAPR on the UL, Direct Fourrier Transform spread OFDM (DFT-s-OFDM) has been widely adopted in 4G and 5G systems. In the LEO UL channel, the device must concentrate its transmission power on a small number of frequency resource blocks to compensate for large propagation loss and improve UL SNR at the base station receiver. Further reduction in PAPR would allow device to transmit with more power using a higher number of resource blocks. One area of research would be to combine coded modulation with DFT-s-OFDM for PAPR optimization. For example, the combination of a properly designed trellis-coded modulation and DFT-s-OFDM (TC-DFT-s-OFDM) may be a candidate to provide low PAPR transmission within a small number of allocated resource blocks. As shown in the figure below, TC-DFT-s-OFDM can provide a lower PAPR than CP-OFDM and DFT-s-OFDM. Figure 11 show that DFT-s-OFDM, and even to a larger extent TC-DFT-s-OFDM, could be used to enhance the DL channel coverage of the LEO system.

More efficient use of transmission power will help close the link budget between the device and the satellite, and also help reduce the level of interference between the satellite and non-satellite systems.

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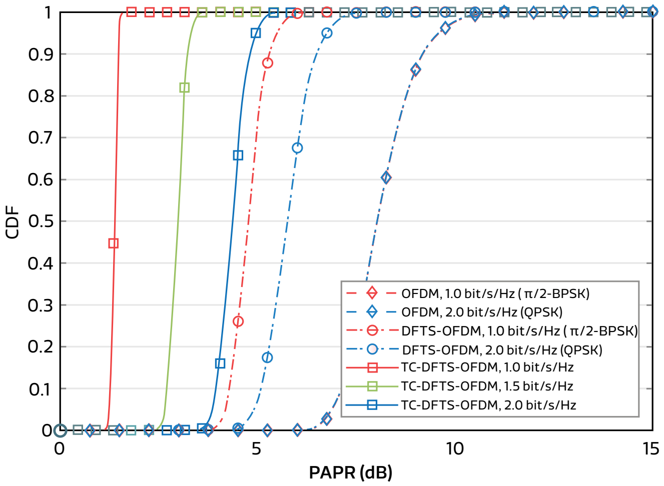

Figure 11: PAPR of OFDM-based systems

4.2 Predictive Mobility Management for Service Continuity

Mobility management is a critical issue for NTN to provide service continuity, where cells can physically move or be switched on or off in time due to satellite movement. As an example, the relative speed of an LEO satellite at 600 km altitude with respect to earth is around 7.56 km/s. With a cell diameter of 50 km, the handovers for the device in connected mode and the changes of camped-cell for the device in idle mode would occur frequently i.e. every few seconds.

In terrestrial networks, the mobility management is mainly based on device measurement. The connected device makes measurements on the neighbor cells, reports its measurements to the network, and based on those may then be handed over by the network to a better cell. In a NTN LEO system, the satellite movement is deterministic: both the cell movement and cell change can be predicted using the satellite ephemeris information and the beam footprint information. 3GPP Release 17 specified enhancements to reduce neighbour cell measurements, as illustrated in Figure 12.

In 5G NR-NTN, for connected mode, the location-based[6] and the time-based[7] triggered events are introduced to facilitate conditional handover[8].

For idle mode, the location-based and time-based (i.e. the time of the serving cell stopping service) are introduced to reduce the measurement overhead for quasi-earth fixed cell.

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[6] i.e. based on device location, a reference location, a distance threshold

[7] i.e. a duration before the serving cell stops service

[8] A mechanism introduced in 5G NR allowing the device to hand itself over to a pre-notified candidate cell when given conditions are fulfilled.

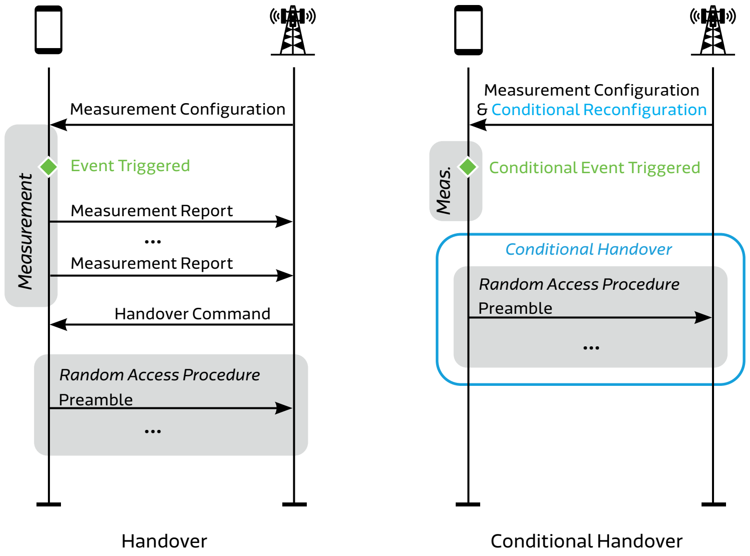

Figure 12: Handover and Conditional Handover procedures

While conditional handover can partially automate mobility in 5G satellite access, in 6G this can be improved to further reduce power consumption and for higher efficiency of radio resources. There is an opportunity in 6G era to re-think mobility aspects specified in 3GPP NTN: within a satellite network, between different satellite networks, and between terrestrial and satellite networks. Assuming the satellite ephemeris/constellation information, beam footprint information and device location are known in the device and in the network, the coverage of the neighbor cell and the arrival time of the next coming cell are predicable. A device could determine when a new serving cell will come into coverage without a need to perform neighbour cell measurement and reporting. This would allow to further mitigate the overhead of measurement/reporting and handover signalling, and to improve device power efficiency. Predictive mobility management for reducing power consumption and utilizating radio resource should be further investigated in 6G NTN.

4.3 Satellite Beam Footprint Adaptation for Coverage Reliability

A key technology to achieve high data rates in 6G NTN is to utilize phased array beamforming. By adjusting the phase of each antenna element, the satellite can steer the beam to illuminate a particular area on the Earths surface for a limited period, concentrating power there. It can also provide more service time without handover interruption compared with using a non-steerable beam.

Although a phased array beamformer can bring benefits in terms of higher data rate and more service time, its beam footprint on the ground is not fixed at different elevation angles, as shown in Figure 13. When the satellite is flying from time t1 to t2, the beam footprint size is shrinking, i.e., the beam footprint decreases as the elevation angle increases.

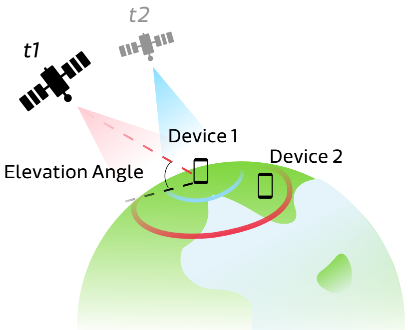

Figure 13: Varying beam footprint at different elevation angles.

In order to provide more reliable beam coverage, maintaining the beam footprint size is a critical issue. A phased array beamformer with control of the number of activated antenna elements can adjust the beam footprint size (i.e., reduce the elongated beam footprint size). Table 3 shows the simulated DL SNR variation for different devices in different locations and the beam footprint varying with the following assumptions:

- The satellite at 600 km altitude is flying over Device 1 and Device 2 and points its beam towards the location of Device 1.
- The desired diameter of beam footprint size is 50 km.
- Device 1 is at the center of the beam footprint, i.e., at the nadir point of satellite at an elevation angle of 90 degree.
- Device 2 is 50 km away from the center of the beam footprint.

The downlink SNRs of Device 1 and of Device 2 are measured when the satellite is at the elevation angles of 30 degree (at time t1) and 90 degree (at time t2), with the results shown in Table 3. For Device 1, the variation of DL SNR between the elevation angles of 30 degree and 90 degree is small. But, for Device 2, the variation of DL SNR between the elevation angles of 30 degree and 90 degree is larger (11dB) without adapting the number of active antenna elements. The DL SNR variation may not impact Device 1 in terms of beam selection, but it may impact Device 2. Device 2 may camp on this beam when the satellite is at time t1, but later it may reselect another beam to camp on due to the lower DL SNR of this beam at time t2. The variation in the beam footprint may cause a device to frequently perform beam reselection or handover, which increases power consumption in the device and incurs higher signalling overhead.

Table 3 DL SNR of Device 1 and Device 2 without adaptation and with adaptation at different elevation angles

	Elevation Angle	DL SNR w/o Adaptation	DL SNR w/ Adaptation
Device 1	30° (t1)	10 dB	14 dB
	90° (t2)	14 dB	14 dB
Device 2	30° (t1)	9 dB	-1 dB
	90° (t2)	-2 dB	-1 dB

For Device 1 and Device 2, the DL SNR (14dB and -1dB, respectively) can be kept at the elevation angles of 30 degree and 90 degree by adaptating the number of active antenna elements. It is more important for Device 2 to avoid camping on this beam from the beginning and subsequently avoid unnecessary beam reselection or handover.

Figure 14 shows the DL SNR with different elevation angles for Device 1 and Device 2. With adaptation, the coverage of a beam is more reliable, i.e., the device could avoid performing unnecessary beam reselection or handover when the satellite is at different elevation angles.

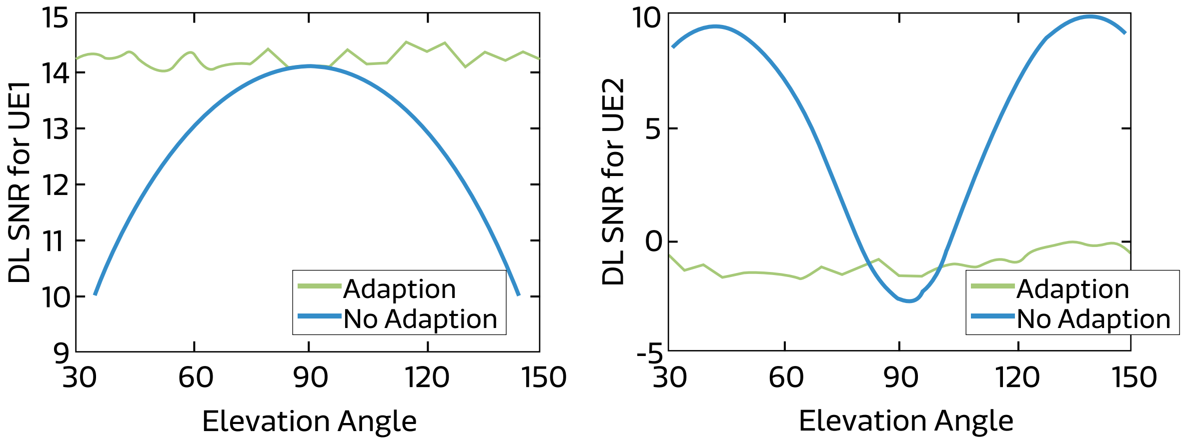

Figure 14: DL SNR variation for Device 1 and Device 2 at different elevation angles.

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Based on the above observations, it is highly desirable to adapt the beam footprint size by controlling the number of active antenna elements. This may require enhancements to form a more uniform beam footprint taking into account the size limitation of the satellite payload, i.e., the beam footprint size is determined by the number of antenna elements. Adjusting the number of active antenna elements at different elevation angles may also require enhancements. A more uniform satellite beam footprint will facilitate the coexistence or spectrum sharing between different satellite networks, and between the TN and NTN. Schemes for satellite beam footprint adaptation aiming at improving coverage reliability should be further explored in 6G NTN.

5. 6G Satellite and Terrestrial Spectrum Sharing

5.1 Motivation

International Telecommunication Union – Radiocommunication (ITU-R) typically allocates spectrum for International Mobile Telecommunications (IMT) (for broadband terrestrial mobile) and satellite usage in an exclusive manner. However, for convergence between satellite and terrestrial networking technologies and common devices, it is worthwhile to consider a target of being able to share the same spectrum assets between terrestrial and satellite deployments in a complementary manner.

This would provide key benefits in terms of maximising the value of available spectrum, further enhancing the overall connectivity experience ubiquitously for the end user. An example scenario: refers to satellite deployments provide wireless coverage in targeted geographical locations by using a spectrum block which is not used by the TN, and vice versa. In the longer term, it will help alleviate the spectrum scarcity problem for the advancement of both satellite and terrestrial networking. This is an area where more research is needed.

Further convergence of NTN and TN technology for 6G could enable a more effective/granular reuse/sharing of spectrum between locations served by terrestrial connectivity and locations served by satellite connectivity, to ensure that there is no negative system performance impact that may be caused by the TN and NTN coexistence. Real-time sensing of TN and NTN, combined with interference mitigation mechanisms using huge satellite antenna arrays with high beamforming gains will be key enablers for a more effective spectrum sharing.

5.2 Interference Problem Analysis

Spectrum sharing relies on effective interference mitigation and management such that all sharing systems can function as if they were not sharing spectrum. Therefore it is important to first analyse the source of interference, using the Signal to Interference and Noise Ratio (SINR) measurement as an important quantifier for each system. Compared to the independent operation of TN and NTN systems, a 10 dB drop in SINR for NTN DL and a 30 dB drop in SINR for NTN UL has been observed in the sharing scenario. Interestingly, there is very little impact on the TN SINR. The interference source on the NTN DL is from the TN base station, where the NTN UL is affected by the TN device. Interference in NTN UL is much more servere, due to the large number of TN devices with omnidirectional antennas transmitting in the UL. This steered our focus towards improving the NTN UL for interference mitigation, such as exploring opportunities triggered by changing the UL interference source so that the TN device's omnidirectional antennas would not be problematic.

Further analysis on the interference source has been conducted using Monte Carlo simulations and it has been observed that most of the interference (up to 90%) is contributed by only 33% of the interference source in the NTN UL. From this we can infer that the large SINR variations between sharing and non-sharing scenarios are caused by only a few highly impacting interference sources, which are not evenly distributed. This narrows down our solution direction to geographically targeting and removing these critical sources to improve the NTN UL system performance.

5.3 Interference Mitigation Solution

The interference analysis section has allowed us to view the interference mitigation problem from two angles: (i) by changing the interference source, and (ii) by geographically removing the interference source.

The interference source can be changed by using a reverse pairing mechanism, where instead of DL channels sharing with each other, the DL shares with an UL channel, as illustrated in Figure 15.

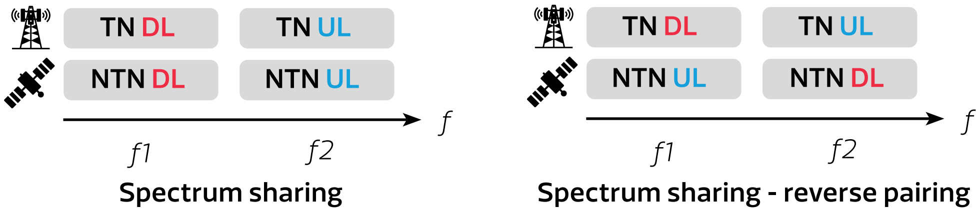

Figure 15. Reverse spectrum sharing

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Originally, in the NTN DL, the interference source came from the TN base station. With the reverse spectrum pairing scheme, where the TN UL will be transmitting at the same time at NTN DL, the interference has switched to the TN device. As a result, the interference in the NTN DL has been successfully mitigated, recovering the 10 dB SINR drop that was caused by spectrum sharing of the original/default scheme. The interference source in NTN UL also switches from TN devices to the TN base station with reverse pairing. This has slightly improved the NTN UL SINR by around 5dB, thanks to fewer base stations (interference sources) compared to the larger number of TN devices, as well as thanks to the downward-pointing base station antennas that will reduce impact for the NTN UL compared to the omni-directional antenna from the device. However, this is still far away from the 30 dB SINR drop, and more interference mitigation techniques are required in the NTN UL.

Building on top of the reverse spectrum pairing mechanism and simulation results, a NTN beam footprint-based frequency re-use is promoted, based on geometric separation, aiming at removing interference in NTN UL, as interference is not evenly distributed. This is based on the size of the NTN beam footprint, defined by its antenna beamwidth. A protection angle is defined and base stations within this footprint region are not allowed to share spectrum, but may choose to use different frequencies, as shown in Figure 16. No base station within the protection zone is allowed to share the NTN spectrum.

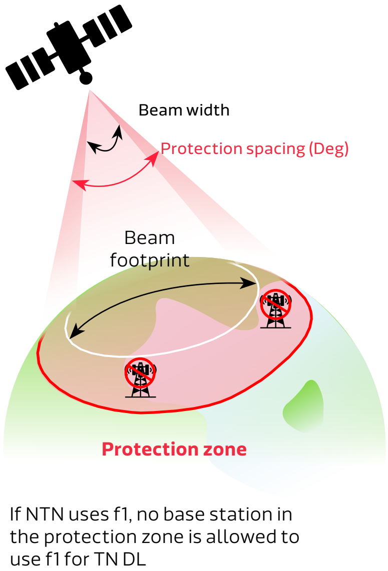

Figure 16. Protection zone

Figure 17 summarizes the average SINR variations with spectrum sharing with the two proposed interference mitigation techniques described above.

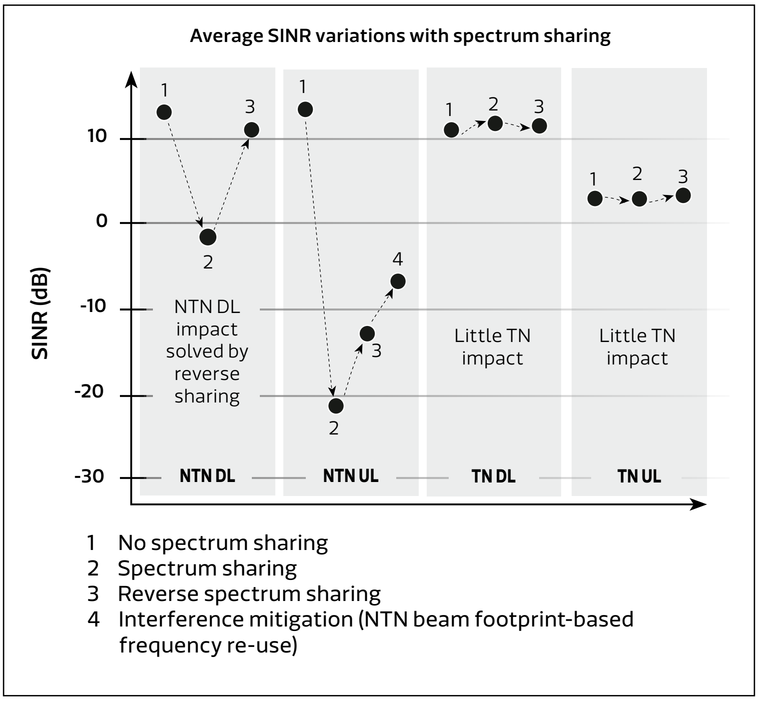

Figure 17: Average SINR variations with spectrum sharing.

The link most susceptible to interference is the NTN UL, even with reverse spectrum pairing and footprint based frequency re-use, there is still a significant SINR gap to close. However, this is a promising research direction to solve the problem of spectrum scarcity and promote cellular and satellite convergence.

6. Conclusion

6G, an IMT2030 and beyond technology, will be commercially available around 2030 as the result of a global standard that will be initiated by 3GPP from 2024. The 6G ecosystem will be more diverse, in terms of e.g., traffic and device types, spectrum ranges and regimes, and networking topologies driving the 6G design. In this paper we have provided our view on some of the fundamental needs, challenges, and technology/industry directions to be considered for the continued evolution of satellite connectivity as part of 6G.

The convergence of terrestrial and satellite networks will be an integral part of 6G, building on the early adoption of open standard satellite communication systems based on 5G technology. This will lead to an expansion of the digital transformation of our society, whether for individual consumers, businesses or governments across various customer markets. It will strive to provide universal and affordable access to the Internet - anywhere and at any time. Convergence of the technology designs of terrestrial and satellite networking is key for enabling the economies of scale needed to drive satellite connectivity to the mass market of end devices. This was a key requirement behind 5G NTN, and will continue to be essential for 6G NTN.

We have identified that providing ubiquitous coverage for smartphones, serving automotive needs, enabling Fixed Wireless Access, and IoT everywhere are key use cases for future satellite connectivity. We have analysed some of the potential 6G NTN technology areas to consider for future 6G technology enhancement in order to enhance the customer connectivity experience for these use cases. In particular, we consider enhancements to waveforms and protocols to improve link budgets, enhancements to mobility management to optimize service continuity, and the usage of phased array beamforming to enable higher data rates.

Access to additional spectrum will be fundamental to continue to enhance both the terrestrial connectivity and satellite connectivity; “complementary” spectrum sharing/reuse between terrestrial and satellite deployments will be key for maximizing spectrum availability for both types of deployments, however this also brings some challenges to ensure that system performance for both terrestrial and satellite deployments can be maintained. The convergence between terrestrial and satellite connectivity technology designs, and the prospect of both types of network being operated by the same entity, provide new opportunities to overcome some of these challenges, and enable a more effective/granular spectrum re/use sharing between terrestrial and satellite deployments.

Overall, satellite connectivity will be a major component of the 6G ecosystem. MediaTek will use its know-how and experience at developing and deploying existing 3GPP 5G IoT and NR NTN technology to ensure that satellite connectivity for 6G will continue to evolve to cater the ever more demanding connectivity expectations of society.

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