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As satellite direct-to-device services move closer to mainstream adoption, two technology options have emerged within the 3GPP ecosystem. The unmodified 4G approach offers broad compatibility with today's smartphones while the more future-proof non-terrestrial network approach promises optimized performance for new devices supporting standardized features from 3GPP Release 17.

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Decades of continuous innovation and investment have produced a mature, globally interoperable mobile ecosystem, projected to reach 8.8 billion subscriptions by the end of 2025 [1]. The cellular technologies standardized by 3GPP (3rd Generation Partnership Project) have enabled high-speed, reliable mobile connectivity in almost every populated region of the world today, but connectivity gaps remain in remote, maritime, mountainous and disaster-hit regions.

In areas where terrestrial coverage is unavailable, direct-to-device (D2D) satellite communication is a viable solution enabled by recent advances in space technology. The introduction of reusable launch vehicles has dramatically lowered launch costs, while narrow spot-beam antennas and advanced radio frequency technologies have enhanced signal strength in a cost-effective way. Modern onboard silicon supports radio access network functions and inter-satellite links. These innovations enable a more effective integration of satellite components into mobile networks, extending coverage and strengthening network resilience.

In alignment with global efforts, 3GPP introduced New Radio Non-Terrestrial Networks (NR-NTN) and Internet of Things Non-Terrestrial Networks (IoT-NTN) as part of Release 17, extending the 5G standard to support reliable communication over satellites. Since then, a variety of satellite services, smartphones and wearables with IoT-NTN capabilities have been launched commercially, primarily to support emergency messaging. Together with partners, Ericsson has successfully demonstrated key 3GPP NTN functionalities [2], laying the groundwork for commercial deployment.

Satellites used for direct-to-device communication

Low Earth orbit (LEO) satellites – Positioned at altitudes below 2,000km and sometimes as low as 180km, LEO satellites benefit from reduced signal delay and lower path loss due to their proximity to Earth. These satellites travel at speeds of approximately 7.8km/s and complete an orbit in about 90 minutes. Due to their limited coverage area, LEO satellites are often deployed in large constellations to provide continuous global or regional coverage.

Geostationary orbit (GEO) satellites – Located at an altitude of 35,768km above the equator, GEO satellites orbit in sync with the Earth's rotation, which makes them appear stationary over a fixed point on Earth. This enables continuous coverage of the same geographic area. Three well-positioned GEO satellites can offer near-global coverage.

Terms and abbreviations

3GPP – 3rd Generation Partnership Project | **ARQ** – Automatic Repeat Request | **CHO** – Conditional Handover | **D2D** – Direct-to-Device |
GEO – Geostationary Orbit | **GNSS** – Global Navigation Satellite System | **HARQ** – Hybrid ARQ | **IMT** – International Mobile Telecommunications |
IoT-NTN – Internet of Things Non-Terrestrial Networks | **ITU** – International Telecommunication Union | **ITU-R** – ITU Radiocommunication Sector |
LEO – Low Earth Orbit | **LTE** – Long Term Evolution | **MNO** – Mobile Network Operator | **MSS** – Mobile-Satellite Service | **NB** – Narrowband |
NR-NTN – New Radio NTN | **NTN** – Non-Terrestrial Networks | **RA** – Random Access | **RLC** – Radio Link Control |
SNO – Satellite Network Operator | **UE** – User Equipment

In parallel with ongoing NTN development, a few industry initiatives are developing low Earth orbit (LEO) satellite constellations capable of delivering standard 4G LTE (Long Term Evolution) signals directly to today's commercially available smartphones. Early use cases, such as emergency alerts and SMS messaging during hurricane disaster relief [3], have demonstrated the practical value and potential of these solutions.

Both the unmodified 4G and the NTN approaches to D2D satellite communication have their own advantages and disadvantages, as shown in the table in **Figure 1**. This article provides a detailed comparison of the two approaches with a particular focus on spectrum and air-interface differences.

Spectrum considerations for satellite direct-to-device communication

Two spectrum access models are available when designing satellite-based D2D systems, each with its own distinct technical and regulatory considerations. The terrestrial mobile spectrum model uses spectrum enabled by the MNO-SNO (mobile network operator – satellite network operator) partnership. The MSS (Mobile-Satellite Service) spectrum model uses the spectrum allocated to MSS in the International Telecommunication Union (ITU) Radio Regulations.

> Both approaches to direct-to-device satellite communication have advantages and disadvantages.

In the terrestrial mobile spectrum model, the SNO obtains authorization to operate within the mobile spectrum that is not currently allocated for satellite services under the ITU Radio Regulations. Currently, operation in these bands is permitted either in a few countries that have established national regulations for D2D satellite communication in terrestrial mobile spectrum bands or under Article 4.4 of the ITU Radio Regulations. In both cases, such use is governed by non-interference, non-protection principles, meaning that satellite systems must avoid causing interference to, and not claim protection from, terrestrial services.

As a result, there are challenges when deploying D2D satellite communication in terrestrial mobile bands. Ensuring the protection of terrestrial networks requires control over satellite transmission parameters. In addition, geographic separation mechanisms must be implemented to prevent co-channel interference with terrestrial systems in adjacent areas. This often requires exclusion zones – areas within a satellite's footprint where transmissions are suppressed to protect terrestrial devices and base stations. The size of these zones is typically equivalent to a satellite spot beam, which can limit the coverage.

Some D2D implementations may seek nationwide, exclusive access to a part of their partner MNO's spectrum. This strategy removes domestic co-channel interference concerns and requires exclusion zones only at border areas. Other implementations may alternatively pursue opportunistic use of underutilized spectrum in unserved and remote regions, enabling reuse without disrupting active terrestrial deployments. This strategy demands high accuracy in spectrum planning, close coordination with the partner MNO and exclusion zones both inside the country and along the borders.

	Unmodified 4G approach	**Non-terrestrial networks approach**
Technology	• Uses terrestrial 4G LTE	• Purpose-built for non-terrestrial environments
Device ecosystem	• Mature and widely available • Massive installed base	• Still developing • Requires new chipset and device readiness
Network design	• Limited design flexibility • Only supported by LEO satellite constellations	• Flexible • Supports a variety of constellations • Can reuse existing satellites for limited services like messaging and voice
Spectrum model	• Terrestrial mobile spectrum enabled by MNO-SNO partnership	• Spectrum allowed for satellite operations
Spectrum regulation	• A few national regulatory frameworks • Non-interference, non-protection basis operation	• Established international regulatory framework
Performance	• May face limitations	• Robust • Optimized in satellite conditions
Outlook	• Short term • Pragmatic solution leveraging existing devices ecosystem	• Long term • Future proof

Figure 1: Comparison of the unmodified 4G and non-terrestrial networks approaches to D2D satellite communication

At the international level, the regulatory landscape is evolving. The ITU-R (ITU Radiocommunication Sector) is considering new MSS allocations in the 700–2,700MHz range to support direct satellite-to-IMT (International Mobile Telecommunications) user equipment (UE) connectivity to complement terrestrial network coverage under WRC-27 (World Radio Conference 2027) Agenda Item 1.13. If these new MSS allocations are adopted, terrestrial services would retain priority over D2D satellite systems, requiring D2D satellite systems to not cause harmful interference to, or claim protection from, stations operating in the terrestrial mobile systems. The primary benefit would be a harmonized global framework to ensure the protection of terrestrial mobile and other incumbent services.

In the MSS spectrum model, D2D services can operate within MSS-designated spectrum such as L and S bands that are internationally allocated for mobile satellite services. D2D deployments in MSS bands benefit from an established

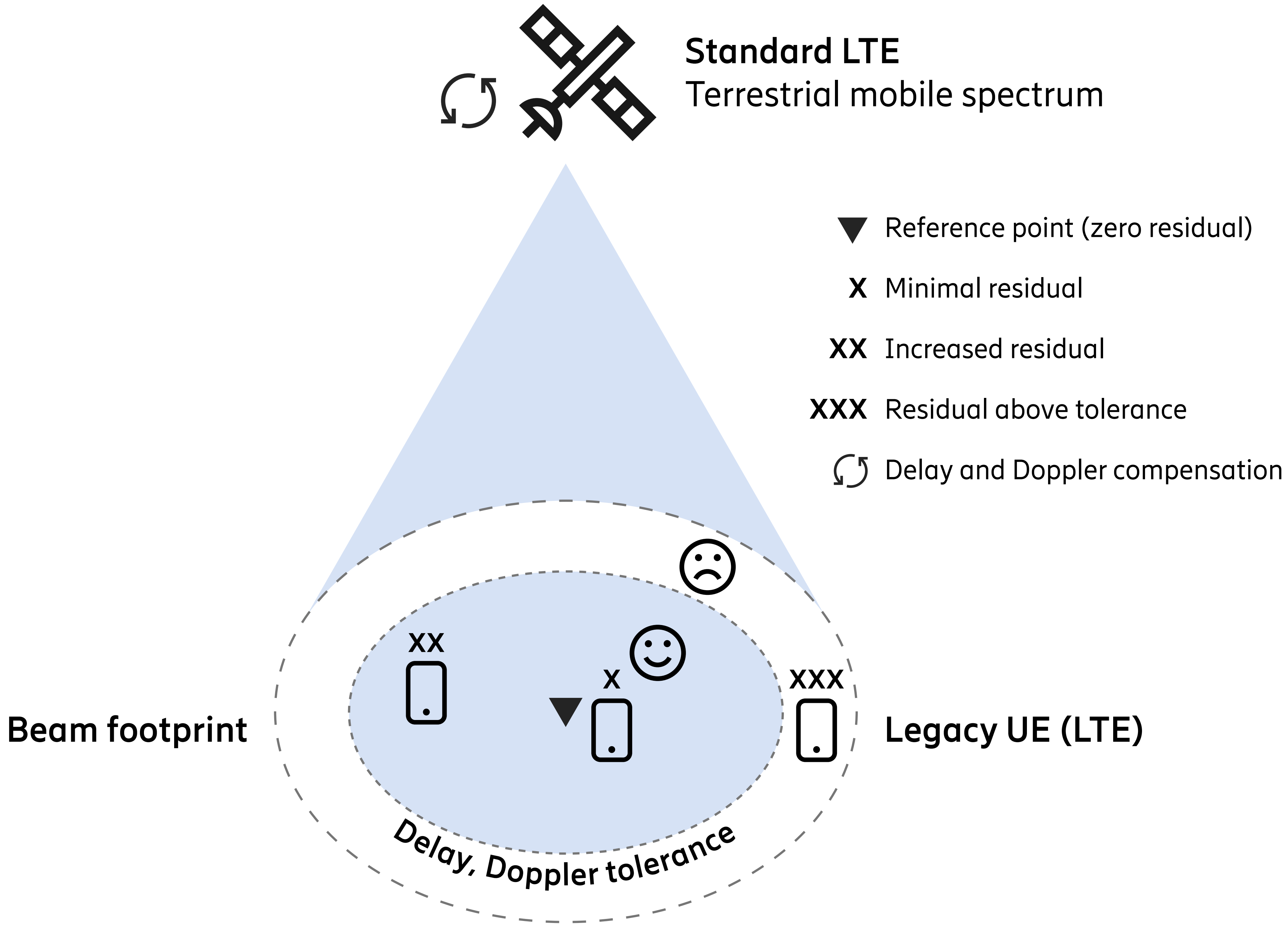

Figure 2: Delay and Doppler compensation schemes in a network-based approach. Note: This figure is for illustrative purposes only. It does not represent actual residual distributions or reference point locations within a beam footprint.

regulatory framework on the coexistence with terrestrial and other incumbent services, enabling a more streamlined approach to interference management.

D2D in MSS spectrum is supported by 3GPP standardization. Starting from Release 17, several MSS bands have been included in the NTN specifications, enabling direct connectivity between satellite access nodes and compatible smartphones, wearables and IoT units. Standardization ensures compatibility across vendors and accelerates ecosystem maturity. However, as 3GPP NTN is still in its early stages, market adoption remains limited, with relatively few devices currently supporting these capabilities. With growing market demand, chipset vendors and original equipment manufacturers are expected to expand MSS support in upcoming product generations.

In summary, both the terrestrial mobile spectrum and MSS spectrum models present viable pathways for expanding mobile coverage from space. The former leverages a mature terrestrial ecosystem but demands sophisticated interference management and complex regulatory navigation. The latter model provides a stable regulatory environment, lower interference risk and 3GPP-backed technical specifications. The success of future D2D deployment will depend on harmonized spectrum policies, robust coexistence management mechanisms and continued advancement in device ecosystems.

Option #1: The unmodified 4G approach

Regulatory agencies in several countries, including the United States [4], Canada [5] and Australia [6], have established national frameworks that permit SNOs to utilize terrestrial mobile spectrum to provide supplementary mobile coverage from space. A few industry initiatives are currently deploying LEO constellations to provide such cellular coverage using a standard LTE air interface. These systems enable D2D connectivity to today’s commercially available smartphones, allowing users to connect without needing new hardware and therefore accelerating the user adoption.

Using the terrestrial air interface for satellite purposes presents significant technical challenges, however. LEO satellites operate at much higher altitudes than terrestrial base stations, introducing substantially longer propagation delays. High orbital velocities also generate pronounced Doppler shifts. To support standard LTE handsets, these delays and Doppler effects must be compensated by the network. Using satellite ephemeris data, delays and Doppler shifts can be predicted and corrected for each antenna beam. However, because delay and Doppler shift vary with the user’s position relative to the satellite, such compensation can only be optimized for a single reference point within each beam.

Figure 2 illustrates how residual delays and Doppler shifts increase when moving away from the reference point, potentially exceeding LTE tolerances and causing connection failures. This is particularly troublesome for the random access (RA) procedure, which establishes initial uplink synchronization between the UE and the network. During RA, the UE transmits a predefined preamble to the base station, which uses the preamble to estimate timing offset and initiate synchronization. If the preamble is distorted due to excessive residual delay or Doppler shift, the base station may fail to detect it, resulting in repeated access failures. Ensuring RA reliability requires residual impairments to remain within specifications across the entire beam footprint.

Several system parameters can be adjusted to mitigate these effects. The most straightforward solution is to design the system with smaller beam footprints that make residual delays and Doppler shifts easier to manage. However, smaller beam footprints require larger antennas, which can increase manufacturing and launch costs, as well as introducing additional complexities in design, calibration and integration. Furthermore, maintaining the same

Standardization ensures compatibility across vendors and accelerates ecosystem maturity.

coverage level with smaller beam footprints requires more beams or even additional satellites, further increasing the system cost and complexity. Another approach is to restrict the antenna beam steering to directions where residual delays and Doppler shifts remain within acceptable levels. While this method effectively controls the impact of the residuals, it limits the coverage area of each satellite. To maintain the intended coverage, a larger satellite constellation is required, which again drives up system cost and operational complexity.

Other parameters, such as the operating frequency band and satellite altitude, are less flexible to tune, as they are subject to availability and regulatory approval. Both factors also affect path loss and other characteristics, directly influencing the link quality and overall system performance. These interdependencies among key design parameters mean that optimizing for one constraint may introduce trade-offs elsewhere in the system, often leading to suboptimal system design.

Besides random access, unmodified 4G D2D satellite systems face additional limitations. One example is the HARQ (hybrid automatic repeat request) operation, which handles transmission errors through retransmissions. The HARQ protocol operates in a stop-and-wait manner, and each HARQ process can only be reused once its corresponding feedback is received. If the round-trip delay exceeds the total time allowed by the maximum number of HARQ processes and slot duration, the system may encounter HARQ stalling. In such cases, the base station is unable to transmit new data, due to exhausted HARQ processes still awaiting feedback. To avoid this, the round-trip time must remain within LTE limits, which constrains satellite orbit altitude and elevation angle. Some systems may instead disable HARQ, relying on Radio Link Control (RLC) ARQ (automatic repeat request) for retransmission. While RLC ARQ offers reliability, it introduces higher latency and overhead, reducing overall throughput efficiency.

Another example is mobility management. Handover algorithms in terrestrial networks typically rely on differences in signal strength between the source and target cells. In satellite networks, however, these differences are minimal because the cell diameter is usually much smaller than the satellite's altitude, resulting in similar distances between the satellite and all UE within a cell. Consequently, path loss and signal strength are nearly uniform across the cell. This lack of signal strength gradient hampers the UE's ability to perform accurate measurements, making handover and cell reselection less reliable.

Standard 5G NR can support unmodified satellite-based D2D services, offering more flexibility and capabilities than LTE. However, the fundamental challenges of adapting it for satellite use remain the same.

In summary, unmodified 4G D2D satellite systems represent a significant step in extending the reach of mobile connectivity. By leveraging the installed base of existing smartphones, they enable rapid adoption and potential global reach. However, these benefits come with substantial technical and operational constraints. The narrow design flexibility and inherent limitations of adapting terrestrial protocols to non-terrestrial environments require complex engineering trade-offs, often resulting in suboptimal cost and performance. While such systems have demonstrated the promises of D2D connectivity, their scalability and long-term evolution will depend on the success of addressing these challenges.

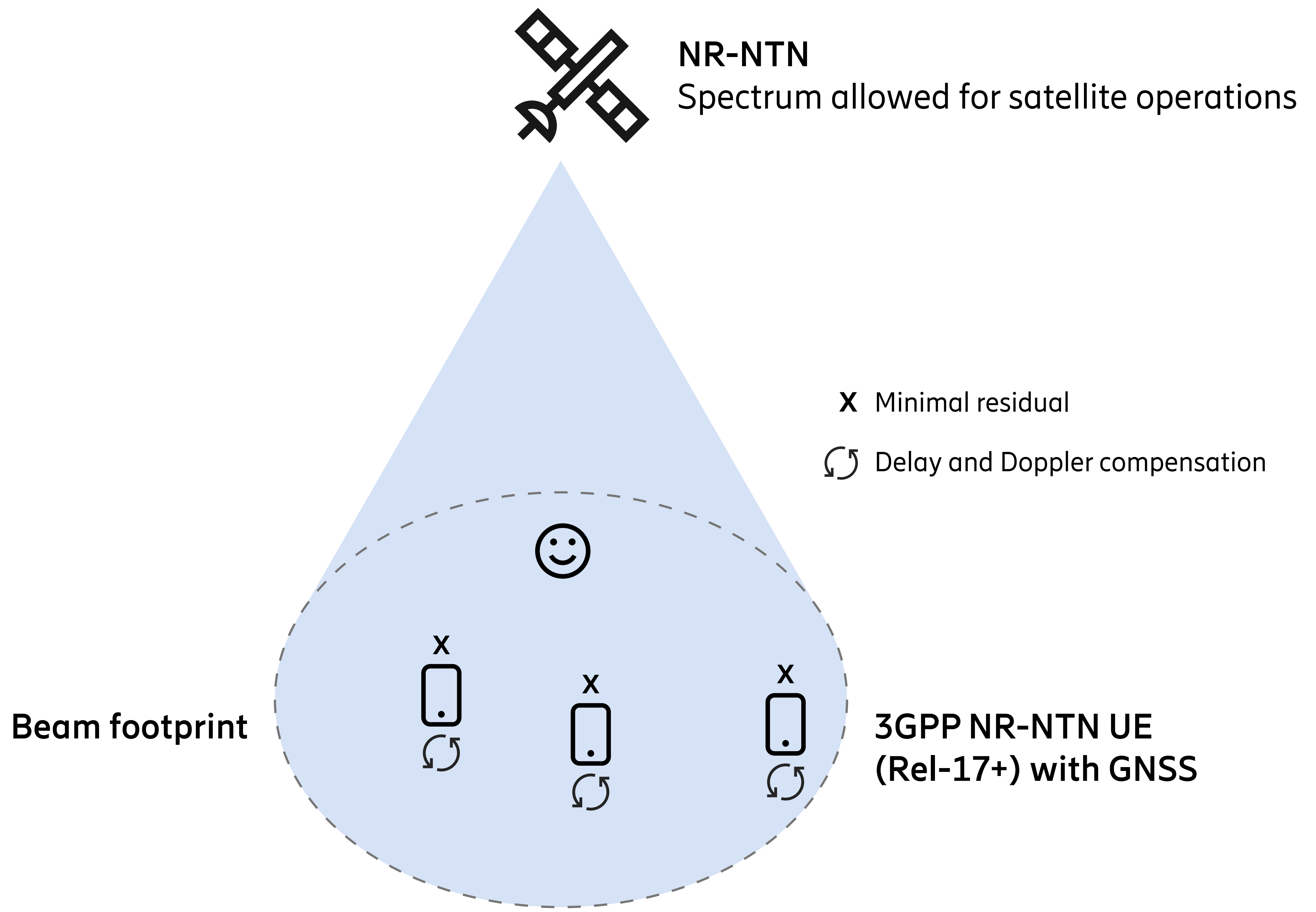

Figure 3: Delay and Doppler compensation schemes in 3GPP NR-NTN systems

Option #2: The non-terrestrial networks approach

3GPP enhanced the 5G NR standards to support satellite-based connectivity in Release 17. While the framework is largely spectrum-agnostic, its current implementation is limited to the MSS bands. Unlike the unmodified 4G approach, NR-NTN requires the UE to actively compensate for delays and Doppler shifts caused by the distance and the relative motion between the satellite and the UE.

To enable this compensation, the UE must first determine its own position using a Global Navigation Satellite System (GNSS) before connecting to the satellite access network. It also receives the satellite's position and velocity vector (ephemeris) and other satellite-related parameters through a new System Information Block broadcast by the satellite access node. Using this information, the UE computes and applies timing and frequency corrections to its uplink transmissions, ensuring any residual impairments are within the tolerances of terrestrial NR, as shown in **Figure 3**. This method removes the constraints on beam footprint due to delay and Doppler errors, allowing more flexible network design across various satellite constellations. It is important to note, however, that these capabilities were introduced in 3GPP Release 17 and are not supported by UE chipsets based on earlier releases.

To further support satellite-based connectivity, 3GPP has also introduced several NTN-specific enhancements. To address HARQ stalling issues, the maximum number of HARQ processes has been increased from 16 to 32, and it is possible to disable the HARQ feedback on a per-process basis. In response to mobility management challenges, particularly for UE in connected mode, 3GPP has enhanced the Conditional Handover (CHO) framework by introducing new time-based and location-based triggering conditions, leveraging the deterministic nature of the satellite movements and the known positioning of antenna beams on Earth.

In time-based CHO, the UE is instructed to execute the handover in a specified time window. This is effective in scenarios involving satellite switch, where one satellite moves out of coverage and is replaced by another. Location-based CHO, on the other hand, relies on the UE estimating its position relative to reference points in the source and target cells. This is particularly suited to conventional mobility scenarios, where the UE moves between adjacent cells. These enhancements are expected to significantly increase the reliability and performance of mobility events in NTN environments.

3GPP continues to introduce new features to enhance the coverage and capacity of non-terrestrial networks.

Beyond Release 17, 3GPP continues to introduce new features to enhance the coverage and capacity of NTN. These include repetitions of certain messages, co-scheduling multiple users via orthogonal cover codes, extending the periodicity of synchronization signals to support beam hopping and NTN support for RedCap (reduced capability) devices. In addition to the NTN bands below 3GHz, new NTN bands above 10GHz have been introduced to support high-bandwidth applications. Looking ahead, future 3GPP releases aim to further expand NTN capabilities with GNSS-resilient operation and broader spectrum support.

In parallel with the development of NR-NTN, 3GPP also introduced support for NTNs in LTE Machine Type Communication and narrowband (NB) IoT technologies as part of Release 17. This effort, known as IoT-NTN, shares many technical similarities with NR-NTN, particularly in its approaches to delay and Doppler compensation. Nevertheless, some special features were needed to cater for the characteristics of IoT devices, such as support for transmission gaps for GNSS measurements, since some IoT devices may not be able to perform simultaneous GNSS and IoT-NTN operations.

NB-IoT was originally designed for low-complexity IoT devices and is generally not supported by mainstream smartphones. However, several chipset manufacturers have recently begun integrating NB-IoT functionality into smartphone platforms. This shift is driven by the realization that NB-IoT-NTN is well-suited for providing basic services such as text messaging via existing geostationary orbit (GEO) satellites. Thanks to its narrow bandwidth requirements, GEO operators can readily accommodate NB-IoT-NTN within their existing spectrum assets. In addition, its built-in coverage enhancement techniques help to overcome the enormous path loss inherent to the long distances involved. Commercial NB-IoT-NTN services have already been launched in several countries [7], enabling everyday satellite connectivity beyond emergency scenarios on compatible devices.

In short, NR-NTN and IoT-NTN mark a significant milestone in the integration of non-terrestrial elements into the broader 5G ecosystem. They enable reliable satellite-based services across various orbits, extending coverage to remote areas. However, adoption remains in the early stages, with limited availability of compatible devices and supporting satellite networks. The long-term success of 3GPP NTN will depend on the continued development and widespread adoption of a robust device and network ecosystem.

Conclusion

Of the two satellite-based direct-to-device (D2D) models using 3GPP technologies, the non-terrestrial network (NTN) approach stands out as the more forward-looking and scalable solution. Purpose-built for non-terrestrial environments, it offers greater flexibility to support a variety of satellite constellations and enables more robust performance. In contrast, the unmodified 4G approach holds a clear advantage in device ecosystem maturity and a lower user-adoption barrier, benefiting from compatibility with today's commercially available smartphones.

Looking further ahead, 6G is expected to incorporate NTN support from the start.

Looking further ahead, 6G is expected to incorporate NTN support from the start. Building on the strong foundation of New Radio NTN, 6G will introduce advanced capabilities such as Global Navigation Satellite System-independent operation for increased resilience and multi-radio access technology spectrum sharing for smooth migration. Realizing the full potential of D2D satellite technology and delivering global, resilient and interoperable connectivity in the 6G era require close collaboration across the telecom, satellite and device ecosystems. Coordinated efforts to advance chipset and device readiness, deploy scalable satellite infrastructure, and tightly integrate with terrestrial networks are essential to accelerate 3GPP NTN commercialization. With unified industry commitment, 3GPP NTN will serve as an important step toward ubiquitous global connectivity.

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