



# Independent study on sharing between satellites and terrestrial mobile networks in the future

A report prepared by Real Wireless for UK Spectrum Policy  
Forum (UK SPF)

A report from Real Wireless

Real Wireless Ltd  
PO Box 2218  
Pulborough  
West Sussex  
RH20 4XB  
United Kingdom

t +44 207 117 8514  
f +44 808 280 0142  
e [info@real-wireless.com](mailto:info@real-wireless.com)  
w [real-wireless.com](http://real-wireless.com)  
in [real-wireless](https://www.linkedin.com/company/real-wireless)

## Version control

| Item            | Description                                                                                   |
|-----------------|-----------------------------------------------------------------------------------------------|
| Source          | Real Wireless                                                                                 |
| Client          | UK Spectrum Policy Forum                                                                      |
| Report title    | Independent study on sharing between satellites and terrestrial mobile networks in the future |
| Sub title       | A report prepared by Real Wireless for UK Spectrum Policy Forum (UK SPF)                      |
| Issue date      | November 2025                                                                                 |
| Document status | Final                                                                                         |

| Version | Date       | Comment                                            |
|---------|------------|----------------------------------------------------|
| 1.0     | 27/10/2025 | First draft issued to UK SPF                       |
| 1.1     | 09/11/2025 | Final report Issued to UK SPF                      |
| 1.3     | 11/11/2025 | Final report with text amendments issued to UK SPF |

| Document management | Date       | Name                                  | Position                                                                                         |
|---------------------|------------|---------------------------------------|--------------------------------------------------------------------------------------------------|
| Document prepared   | 23/10/2025 | Dr Abhaya Sumanasena<br>Julius Robson | Head of Policy and Regulation,<br>Real Wireless<br>Subject Matter Expert (3GPP<br>NTN standards) |
| Document reviewed   | 26/10/2025 | Simon Fletcher<br>Prof. Barry Evans   | CEO, Real Wireless<br>University of Surrey                                                       |

## About Real Wireless

Real Wireless is the world's leading independent wireless advisory firm. Its network of experts includes engineers, physicists, economists, security advisors, business strategists and deployment specialists. Real Wireless clients benefit from a comprehensive portfolio of specialists and custom tools that analyse radio network performance, techno-economic impact and the business model implications of wireless systems. With this unmatched resource Real Wireless is able to advise the industry and all user groups, spanning businesses to governments, mobile operators, regulators and technology companies on every aspect of wireless technology.

Real Wireless has applied this unique range of technical and strategic expertise to some of the UK's biggest wireless infrastructure projects – from major stadium connectivity to shopping malls to transport systems — and has worked with operators, vendors and regulators on all forms of wireless connectivity. It has also advised governments and the European Union on the technical, social and economic implications of communications policy.

Real Wireless experts help clients to understand, select and deploy technology according to need; we deliver truly independent advice as we are not affiliated with any association, company or proprietary standard. That is why, with 5G now being deployed and 6G on the far horizon, Real Wireless is best placed to guide and advise businesses on the choices and opportunities next generation communications systems will bring.

## For details contact us at:

**e**      [info@real-wireless.com](mailto:info@real-wireless.com)  
**w**      [www.real-wireless.com](http://www.real-wireless.com)  
**in**     [real-wireless](https://www.linkedin.com/company/real-wireless)

## About UK Spectrum Policy Forum

Set up at the request of Government the purpose of the Spectrum Policy Forum is to be a pro-active industry-led 'sounding board' to UK Government and Ofcom on future policy and approaches on spectrum and a cross-industry 'agent' for promoting the role of spectrum in society and the maximisation of its economic and social value to the UK. We do this by exchanging news and views on developments in using spectrum, drawing on our industry expertise from around the world.

The Forum is open to the full range of UK spectrum users. Our members currently include over 240 companies and organisations with an interest in using spectrum for a diverse range of applications. In this context the term 'spectrum users' is to be interpreted in the widest sense - including all industry sectors which use (or will use) wireless techniques and organisations involved in the entire value chain in these activities.

The Steering Board ensure that the work of the Forum is properly framed, work items expedited in the correct manner and suitably resourced, and monitor progress on the delivery of the agreed work packages. The current members of the Steering Board are:

- Department for Science, Innovation and Technology (DSIT)
- Ofcom
- Ministry of Defence (MoD)
- Everyone TV
- BBC
- BT Group
- Digital UK
- HPE
- FarrPoint
- Nokia
- Qualcomm
- Real Wireless
- Samsung
- VMO2
- Vodafone Three
- StrathSDR

## Executive summary

With the evolution of satellite technologies and the launch of LEO satellites in new mega constellations, Satellite Direct to Device (D2D) has gained new life. The integration of satellite D2D connectivity into mass market products like smartphones has the potential to unlock a vast new user base for satellite services, reaching billions of mobile phone users. While traditional revenue generators in the satellite communications industry have experienced a decline in recent years, the satellite broadband internet market, driven by next-generation D2D Mobile satellite and IoT services, is witnessing significant growth.

With the growing interest in the topic, Real Wireless has been commissioned by the UK SPF to conduct an independent study on sharing between satellites and terrestrial mobile networks in the future. Our analysis examines the key factors influencing satellite D2D business case viability, including end customer use cases and service level expectations, spectrum availability and regulation, partnership options, standards roadmaps, devices and chipset considerations, performance analysis and spectrum requirements.

### End customer use cases

The four main D2D use cases are: coverage extension beyond terrestrial networks, enhanced availability and reliability for emergency services, enhanced resilience for terrestrial network outage and IoT connectivity. Satellite backhauling with VSAT terminals is an adjacent use case with a converging technology ecosystem. It offloads some traffic which may otherwise require D2D, and addresses indoor and onboard scenarios that D2D cannot. D2D services range from delay tolerant and low-rate messaging and IoT, which are possible to serve at an early stage of constellation rollout. Delay sensitive services like voice are possible with single digit kbps rates, but do require continuous connectivity, which implies a minimum number of satellites in the case of a LEO constellation. Data is usable with 100s kbps, but Mbps would be required for parity with terrestrial networks. For the coverage extension use case, network capacity can be low and interworking is not critical. The other use cases each have their challenge. Increased availability for emergency services requires seamless satellite-terrestrial interworking. A terrestrial network (TN) outage would create an enormous traffic demand, requiring either capacity to match, or effective prioritisation mechanisms for critical users and services.

### Satellite Network Operator partnership options

Considering recent commercial progress for satellite D2D, the report identifies four ways Satellite Network Operators (SNOs) have and are partnering to provide D2D services and integrate them with the terrestrial smartphone ecosystem. The first of these is SNO-proprietary: D2D has been available for decades in the form of the constellation-proprietary satphone, prior the current interest in smartphone integration. The second partnership has the SNO partner with a device vendor to integrate that proprietary technology into a smartphone, as was the case for the iPhone14. A similar Android-centric offer with Iridium was abandoned, citing a market preference for standards. A third SNO partnership model is SNOs with MNOs in their IMT spectrum with the direct to unmodified terrestrial LTE approach. This has immediate market addressability, but the SNO takes on most of the risk – an agile approach for disruptors. Incumbent SNOs are bringing their MSS spectrum to the table with the fourth type of partnership. This is based on 3GPP's Non Terrestrial Network (NTN) features which shares complexity between network and UE, and puts the ongoing development and maintenance of the technology into an open standards process. MSS-based IoT-NTN and IMT-based LTE-TN approaches should now scale up with more satellites, more MNO partnerships and more subscribers. There have been proposals in 3GPP to add D2D IMT bands to the NR-NTN specifications and IMT D2D SNOs have also now acquired their own MSS spectrum. The adoption of NR-NTN for both IMT and MSS spectrum would seem likely in the medium term.

## Performance requirements

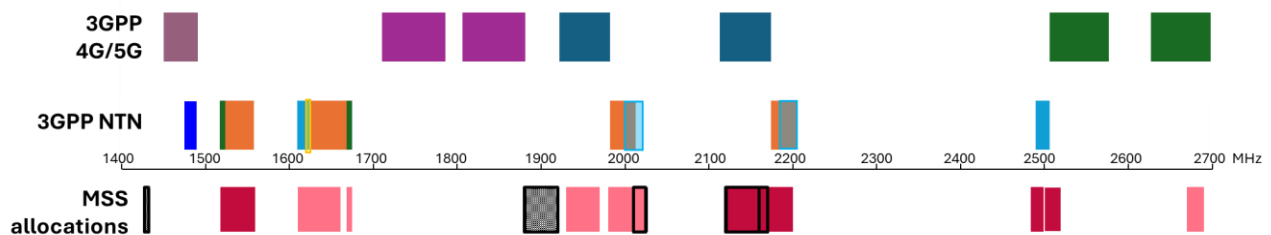
Within the D2D use cases, we have proposed quality of service expectations for the main services of IoT/messaging, voice and data. We have also analysed 3GPP's assessment of spectrum efficiency for its NR-NTN technology, which informs the channel bandwidths and cell densities needed to meet the minimum data rates for the above services. 3GPP's baseline assumption of a 45 km-diameter NTN cell required 30+30 MHz of spectrum to meet the IMT-2020 rural satellite area capacity requirement of 8 kbps/km<sup>2</sup>. The same capacity and user throughputs could be achieved with less spectrum and a higher cell density, implying smaller satellite beam footprints, enabled by larger antenna arrays and/or lower orbits. Starlink v2 has around 5x cell density of the 3GPP baseline, and AST around 12x. All else being equal, this indicates the IMT2020 satellite requirements could be met with 3-6 MHz with these denser networks.

In our analysis, we provide example throughput levels achievable and explain why real deployments perform worse than the best case. We also provide a high-level comparison of direct-to-TN-LTE UEs in IMT spectrum and 3GPP's NR-NTN standard, which includes several enhancements and optimisations on top of the terrestrial protocol.

Spectral efficiency in D2D networks will be lower than in terrestrial networks. The IMT-2020 terrestrial requirements for average spectral efficiency in Rural are 3.3 and 1.6 bit/s/Hz/TRxP for downlink and uplink, respectively. The comparable IMT-2020-satellite requirements are 0.5 and 0.1 bit/s/Hz/TRxP.

## Spectrum Implications

The two spectrum access options for satellite D2D are MSS bands and IMT bands. Existing MSS bands have generally already undergone the necessary regulatory studies, as these bands have been allocated and planned for MSS service. Therefore, they can be authorised for D2D operation through the existing licensing process. As shown in the figure, 3GPP has standardised most of the MSS bands between 1.4 GHz and 2.6 GHz for NTN, providing chipset vendors with a signal to consider these bands in their roadmaps. In contrast, the second option, D2D operations in IMT bands, requires further regulatory work to enable D2D operations.



An optimal spectrum approach provides enough MHz of IMT to benefit from the early disruptive approach, whilst sufficient MSS should also make attractive the evolution onto a 3GPP NTN ecosystem in MSS spectrum.

## Contents

|           |                                                                                                                                  |           |
|-----------|----------------------------------------------------------------------------------------------------------------------------------|-----------|
| <b>1.</b> | <b>Introduction .....</b>                                                                                                        | <b>3</b>  |
| 1.1       | Definition of direct-to-device communications and Non-Terrestrial Networks (NTN).....                                            | 3         |
| 1.2       | Our approach and organisation of the report to provide an overview of the main elements in the Satellite D2D business case ..... | 4         |
| <b>2.</b> | <b>End customer use case(s) and service level expectation .....</b>                                                              | <b>5</b>  |
| 2.1       | Service considerations for each use case.....                                                                                    | 6         |
| 2.1.1     | TN Coverage enhancement .....                                                                                                    | 6         |
| 2.1.2     | Enhanced Availability and reliability for emergency services.....                                                                | 7         |
| 2.1.3     | Resilience to TN outages.....                                                                                                    | 7         |
| 2.1.4     | IoT .....                                                                                                                        | 7         |
| 2.1.5     | Automotive .....                                                                                                                 | 8         |
| 2.2       | Performance requirements from ITU.....                                                                                           | 8         |
| 2.3       | Summary of use cases and services .....                                                                                          | 9         |
| <b>3.</b> | <b>Spectrum availability and regulation .....</b>                                                                                | <b>10</b> |
| 3.1       | D2D in MSS bands .....                                                                                                           | 10        |
| 3.2       | D2D in MS bands .....                                                                                                            | 10        |
| 3.3       | Spectrum bands analysis .....                                                                                                    | 12        |
| 3.4       | Summary .....                                                                                                                    | 16        |
| <b>4.</b> | <b>Service providers and SNO partnership options to reach customers .....</b>                                                    | <b>17</b> |
| 4.1       | SNO partner with device vendor. e.g. Globalstar-Apple .....                                                                      | 18        |
| 4.2       | SNO Partner with MNO sharing their IMT spectrum. e.g. Starlink-TMO US.....                                                       | 18        |
| 4.3       | SNO with MSS spectrum partners with MNO .....                                                                                    | 19        |
| 4.4       | Summary .....                                                                                                                    | 20        |
| <b>5.</b> | <b>Technology standards roadmaps .....</b>                                                                                       | <b>21</b> |
| 5.1       | Technical challenges of Satellite D2D and how they are solved.....                                                               | 21        |
| 5.1.1     | Access link in NTN and for direct to TN UEs .....                                                                                | 21        |
| 5.1.2     | 3GPP NTN roadmap .....                                                                                                           | 22        |
| 5.2       | Handovers and LEO Satellite switching .....                                                                                      | 22        |
| 5.3       | NTN-TN Integration .....                                                                                                         | 23        |
| 5.3.1     | Single PLMN .....                                                                                                                | 24        |
| 5.3.2     | Multiple Operator Core Networks (MOCN) .....                                                                                     | 24        |
| 5.3.3     | Roaming .....                                                                                                                    | 25        |
| 5.4       | Other Notable NTN Enhancements in 3GPP .....                                                                                     | 25        |
| 5.4.1     | GNSS resilience Rel20 - GNSS still needed, but keeps working in temporary outage .....                                           | 25        |
| 5.4.2     | TDD mode for IoT NTN.....                                                                                                        | 26        |

|           |                                                                         |           |
|-----------|-------------------------------------------------------------------------|-----------|
| 5.4.3     | IMS voice calls over GSO for NB-IoT-NTN, and ultra low rate Codec ..... | 26        |
| 5.4.4     | Low Selection PLMN rules to avoid D2D overload .....                    | 26        |
| 5.4.5     | 6G NTN .....                                                            | 26        |
| 5.5       | IMT2020 Satellite and IMT2030 .....                                     | 27        |
| <b>6.</b> | <b>Devices and chipset considerations .....</b>                         | <b>28</b> |
| 6.1       | Chipsets underpin the smartphone ecosystem .....                        | 28        |
| 6.2       | Key elements of the Smartphone chipset .....                            | 28        |
| 6.3       | Timing of 3GPP NTN chipset and devices availability .....               | 29        |
| <b>7.</b> | <b>Performance analysis and spectrum requirements.....</b>              | <b>30</b> |
| 7.1       | User and Cell Spectral efficiency and throughput.....                   | 30        |
| 7.2       | Area traffic capacity .....                                             | 32        |
| 7.3       | Increasing area capacity .....                                          | 32        |
| 7.3.1     | Channel bandwidth.....                                                  | 33        |
| 7.3.2     | Spectral efficiency.....                                                | 33        |
| 7.3.3     | Cell density.....                                                       | 34        |
| 7.4       | Summary of performance .....                                            | 35        |
| <b>8.</b> | <b>Conclusions .....</b>                                                | <b>35</b> |
| 8.1       | Main conclusions of the study .....                                     | 35        |
| 8.2       | Recommendations for future work.....                                    | 37        |
|           | <b>Appendix A Abbreviations .....</b>                                   | <b>38</b> |
|           | <b>References.....</b>                                                  | <b>41</b> |

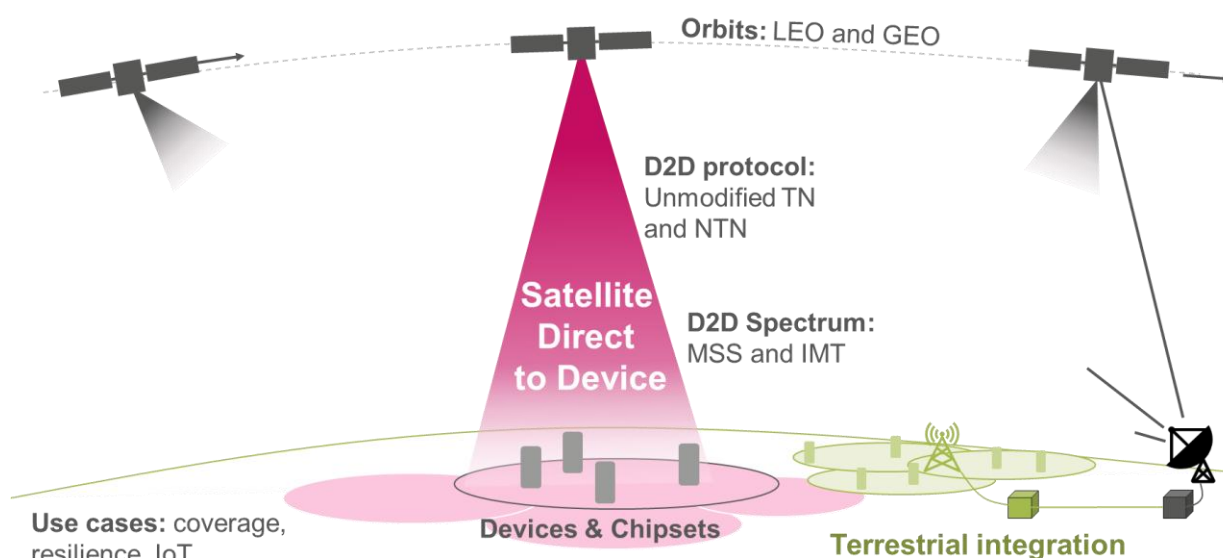
## 1. Introduction

Direct-to-device (D2D) satellite communications have been in existence for decades via proprietary legacy satCom phones. However, with the evolution of satellite technologies and the launch of Low Earth Orbit (LEO) satellites in new mega constellations, Satellite D2D has gained new life with the integration of next-generation satellite D2D into smartphones. The next generation of D2D satellite communications is an emerging technology with much discussion around its potential to provide a layer of global coverage to augment and add resilience to existing terrestrial network coverage. Looking ahead to 2030, key drivers for satellite communications will include expanding broadband access for millions of new consumers and businesses through constellations like Starlink, OneWeb, and Kuiper, especially in regions lacking fibre infrastructure. If technical and commercial challenges can be addressed, direct smartphone connectivity has the potential to unlock a vast new user base for satellite services, reaching billions of mobile phone users [1][2]. There are a number of technology approaches to D2D which each have different implications on spectrum, device availability timeframe as well as cost and risk for the satellite network operator (SNO). The wide interest in satellite D2D is also bringing the topic of access to spectrum into WRC-27 where the use of Mobile Satellite Service (MSS) and International Mobile Telecommunications (IMT) spectrum bands for these services is already set out in three agenda items.

The integration of satellite and Terrestrial Networks (TN) has become increasingly important, especially for enhancing mobile communication in rural and underserved areas through satellite-based D2D services. With the growing interest in the topic, Real Wireless has been commissioned by the UK SPF to conduct an independent study on Sharing between satellites and terrestrial mobile networks in the future.

We first introduce the terminology we use in the report, in line with the industry. We then identify different elements in the satellite D2D business case in the UK and their interactions.

### 1.1 Definition of direct-to-device communications and Non-Terrestrial Networks (NTN)



**Figure 1: Key Issues For Satellite-Terrestrial Sharing**

Satellite-enabled cellular connectivity comes in many forms. D2D refers to a satellite network or service providing direct connectivity between satellites and user devices. The terms “direct communication”, “Direct to Cell (D2C),” and “Direct to Device (D2D)” are used synonymously in the literature [3]. In the World Radio Conference 2023 (WRC-23) D2D was introduced mainly to complement terrestrial IMT

network coverage; for instance, the complementary coverage from space to areas could include high mountains, remote islands and deserts. Additionally, satellite systems can provide alternative network resilience in the event of failure of terrestrial IMT base stations due to unexpected incidents, such as natural disasters or network outages. In most cases, a partnership between an MNO and SNO is required for this to work. Usually, there has to be one operator responsible for the operation or managing the traffic. This will enable the operation of these devices under the same parameters as those for the supported terrestrial networks, according to the existing regulations.

The Third Generation Partnership Project (3GPP) defines NTN as “*networks or segments of networks that use either Uncrewed Aircraft Systems (UAS) operating typically between 8 and 50 km altitudes, including High Altitude Platforms (HAPs) or satellites in different constellations to carry a transmission equipment relay node or a base station*”. In this report NTN refers specifically to 3GPP’s NTN feature set to support satellite communications. 3GPP made enhancements to the 5G New Radio (NR) air interface protocol from Rel-17 onwards to support broadband satellite D2D (known as NR-NTN), and to the LTE Narrow Band Internet-of-Things (NB-IoT) air interface protocol from Rel-17 onwards to support narrowband satellite D2D (known as IoT-NTN).

Our focus in this study is limited to satellite D2D services.

## **1.2 Our approach and organisation of the report to provide an overview of the main elements in the Satellite D2D business case**

The main objective of the study is to explore the business case of satellite D2D . A business case has many components. We identify those components and present a detailed discussion of each business case in each section of the report.

- End customer use cases and service level expectations (section 2)
- Spectrum availability and regulation (section 3)
- Service providers and SNO partnership options to reach customers (section 4)
- Technology standards roadmaps (section 5)
- Devices and chipset considerations (section 5)
- Performance analysis and spectrum requirements (section 7)
- Finally, section 8 provides the overall findings of the report.

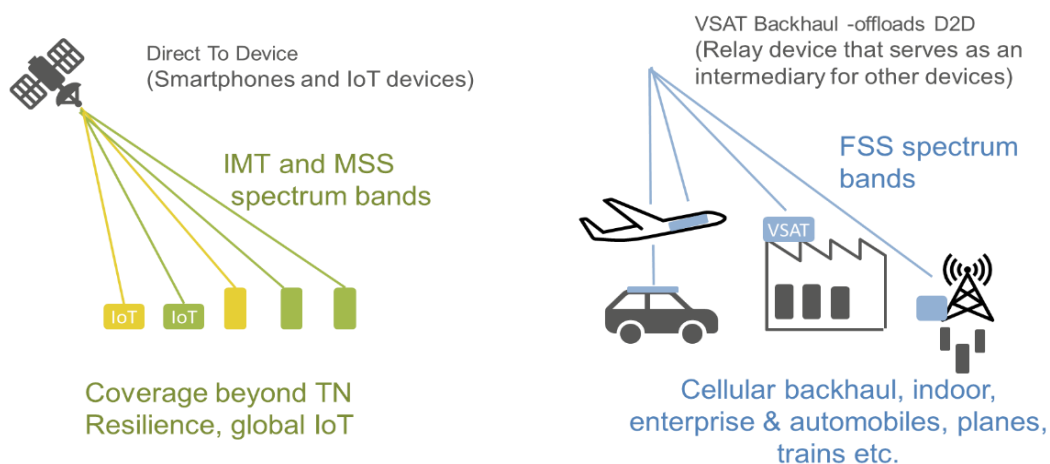
## 2. End customer use case(s) and service level expectation

The main use cases for satellite D2D are:

1. **Coverage extension:** The provision of mobile coverage and connectivity to remote or hard to reach areas where it is currently uneconomical to deploy traditional terrestrial networks.
2. **Enhanced availability and reliability** for access to and assistance from the emergency services during emergency situations.
3. **Resilience:** Improved network resilience for terrestrial networks enabling continuity of service during disruptions such as e.g. natural disasters and interruption to base station power supplies
4. **IoT:** Beyond consumer devices, future innovation and market opportunities across different sectors include providing space connectivity for IoT devices.

Use cases 2 and 3 potentially overlap: Enhanced availability and reliability means fewer and less frequent connectivity outages. Resilience is the ability to recover from a failure or outage. If it were possible for D2D to seamlessly recover connectivity in the event of a TN outage with zero failover time, then it would amount to increase availability of the connectivity. However, resilience with delays is still beneficial and represents a use case in itself.

Satellite can also be used for several “backhauling” type use cases in Fixed Satellite Service (FSS) spectrum shown in Figure 2. These are not D2D but are a side consideration as 1) They also have a part to play in extending mobile coverage to remote areas, particularly to indoor devices and those on moving platforms, effectively offloading D2D, and 2) there are synergies with the D2D technology ecosystem: Starlink is first and foremost an FSS Very Small Aperture Terminal (VSAT) offering, and in 3GPP, Frequency Range 2<sup>1</sup> (FR2)-NTN is driving solutions for challenges which are more acute in FSS – such as Global Navigation Satellite System (GNSS) resilience. The automotive use case potentially comprises both backhauling and D2D elements: the car itself may be viewed as a device or ‘thing’, needing connectivity for navigation, system updates, servicing data etc. A broadband satellite connection could also be relayed over Wi-Fi to smartphones and other consumer devices for passenger use. The automotive market has the potential for scale, but the lack of Starlink terminals in Tesla cars indicates barriers and/or a lack of market drivers.



**Figure 2: Direct to Device in IMT and MSS bands vs VSAT ‘backhauling’ in FSS bands**

<sup>1</sup> Frequency Range 2 or FR2 refers to 10700 MHz – 30000 MHz

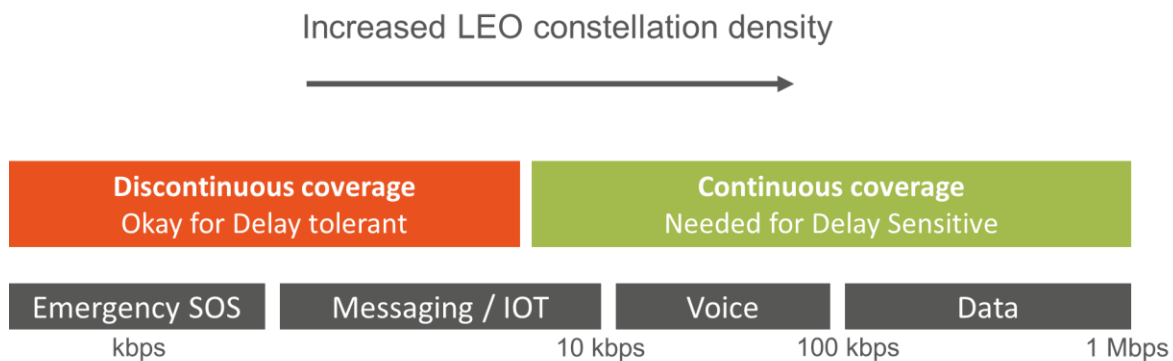
## 2.1 Service considerations for each use case

### 2.1.1 TN Coverage enhancement

In the TN coverage enhancement use case, D2D provides services where the terrestrial network does not. Initial services offerings with immature constellations have been limited in both their throughput but also in the continuity of their coverage. A LEO constellation can in theory provide global coverage with just one satellite – but there will be several hours wait between flyovers at any given location. Densifying the constellation reduces the gaps between flyovers, and at some point continuous coverage is achieved at the desired latitudes. Densifying further provides more payload resources to serve traffic demand and can help to increase network capacity and per-user data rates.

The next section provides a potted history of the evolution of D2D networks and the services provided. The initial service offering from the iPhone14 was SOS messaging to be used only when the terrestrial emergency calling was not available. This evolved into location sharing and low rate messaging, all of which require only a low network capacity and are tolerant to delays whilst waiting for a satellites to come into view. As networks densify to provide more capacity and continuous coverage, voice and app-specific data services are being offered.

Figure 3 summarises this evolving of service offering as LEO constellations densify, with indicative user data rates. This coverage extension use case presumes there are no terrestrial services at all where D2D is used. For the delay tolerant services, anything is better than nothing, and consumers will benefit from any messaging capability. However, for delay sensitive services like voice and some mobile data applications, it is better to deny service than to frustrate users with fruitless attempts.



**Figure 3: D2D services and expectations**

Service expectations can vary depending on the specific location, whether urban or rural, and whether terrestrial services are available. For instance, in areas without terrestrial connectivity, consumers may value low data rate applications. In emergencies or during temporary outages, government services would also benefit from low data rate applications. Further, use cases from other countries may not necessarily translate to the UK due to differences in size and regulatory structures. For example, large geographical coverage may be appealing in countries like Australia or the USA. However, according to Ofcom data published in May 2025, around 96% of the UK landmass is expected to have good outdoor 4G coverage from at least one mobile network operator. Across all technologies mobile network operators are maintaining coverage of at least 99% outside UK premises [4], and this is expected to increase. Although the opportunity to provide coverage in areas without terrestrial service in the UK is limited, extending coverage to the last few percent of the UK population is very costly and may necessitate the use of satellite connectivity.

D2D coverage may serve an additional use case of discovering new locations with sufficient demand to justify investment in terrestrial infrastructure. However, it may not be in an SNO's interest to share such information with terrestrial MNOs if it undermines their business case. We show later that D2D is likely to be 6-16x less spectrally efficient than a rural cell, so overall spectral usage will benefit from a holistic satellite-terrestrial approach. Partnerships and potentially regulation should ensure parties are motivated to share information and optimise the integrated approach.

### **2.1.2 Enhanced Availability and reliability for emergency services**

This use case requires a thin layer of D2D to combine with terrestrial coverage to increase the locations and times that emergency services have connectivity, as well as increasing mean time between connectivity failures. Reliability is subtly different to the resilience use case where D2D is available as a fallback when failures do occur. Increasing uptime implies "seamless" switchover to D2D when needed, without losing connectivity. "seamless" implies no *noticeable* interruption to connectivity in a change of network connection. What is noticeable depends on the service being used. The same messaging, IoT, Voice and data services mentioned previously will be required, but delay tolerance would be reduced for such critical communications.

The Emergency Services Network (ESN) is a critical communications system used by emergency services across Great Britain, which will provide fast, safe, and secure voice, video, and data communications over a 4G network. The ESN aims to cover 97% of Great Britain's landmass and 99% of sealed roads [5]. A satellite-based network is well placed to cover the most difficult-to-reach areas for TNs. The demanded D2D capacity for emergency services in this use case will be lower than other use cases addressing the broader set of citizen mobile subscribers.

### **2.1.3 Resilience to TN outages**

Resilience is the quality of being able to recover gracefully from a failure, and D2D has the potential to provide a fallback in case of a terrestrial network outage. The same service evolution story mentioned above applies – delay tolerant messaging being better than nothing, but delay sensitive services should only be started if they can be sustained. This use case has differing requirements to the enhanced availability for emergency services. Seamless terrestrial-satellite interworking is nice to have but not critical. But demand during a network outage could be enormous, so either D2D would temporarily need very large capacity, or prioritisation and throttling mechanisms would be needed to avoid network being swamped.

### **2.1.4 IoT**

Low power and low cost are more critical in the IoT use case compared to others, so IoT D2D networks may be differently optimised than one targeting broadband. In particular a sparse constellation with discontinuous coverage may be acceptable for some IoT applications which are tolerant to delays of order minutes or even hours.

Connectivity to IoT devices allows for seamless integration with a variety of IoT endpoints, supporting diverse applications in both remote and urban environments. It offers low data rate messaging, making it ideal for intermittent, low-bandwidth communication that is suitable for delay-tolerant use cases. Discontinuous transmission patterns may occur depending on network conditions and device behaviour.

In the UK, utility sectors like water, gas, and electricity are already utilising NTN to improve connectivity for remote infrastructure and enhance emergency resilience.

1. Thames Water partnered with Vodafone Business and CSL Group to upgrade over 3,500 telemetry sites with dual-path connectivity, including satellite fallback. This enhancement enables real-time monitoring and proactive maintenance of their water infrastructure [6].
2. UK Power Networks utilizes satellite backhaul and smart grid telemetry for their substations in remote areas. Their open data dashboards provide operational insights and infrastructure mapping, which support Net Zero planning and improve emergency resilience [7].
3. Vendor case studies indicate that UK gas utilities, including National Grid Gas and Cadent Gas, employ satellite Supervisory Control and Data Acquisition (SCADA) and IoT for monitoring pipelines and telemetry at compressor stations, particularly in regions without terrestrial coverage. These initiatives are part of broader critical infrastructure connectivity programs.
4. On 16 October 2025, the Smart Networks and Services Joint Undertaking (SNS JU) and the European Space Agency (ESA) established a collaboration to accelerate innovation in the integration of terrestrial and non-terrestrial networks for 6G [8]. The partnership plans to undertake comprehensive trials of TN/NTN connectivity for critical industries, including mobility, utilities, agriculture, and media, as well as mobile broadband services for citizens throughout Europe.

## 2.1.5 Automotive

As discussed earlier, satellite connectivity for automotive could be both for the car as an IoT ‘thing’ itself or as a relay to passengers smartphones. The former represents an IoT D2D use case and the latter is more of a VSAT backhaul use case, where FSS spectrum is applicable.

In May 2025, the 5G Automotive Association (5GAA) hosted a global premiere in Paris, showcasing real vehicles that utilise both satellite connectivity and terrestrial 4G/5G networks [9]. The 5GAA’s roadmap anticipates the launch of commercial NTN-enabled services in vehicles by 2027, leveraging the 3GPP Release 17 IoT NTN standards [10].

## 2.2 Performance requirements from ITU

International Telecommunication Union (ITU) Working Party (WP) 4B evaluated satellite IMT-2020 candidate technology through the Independent Evaluation Group (IEG) [11]. Some of the performance requirements of IMT-2020 set by the ITU-R are shown in Table 1

**Table 1: IMT-2020 performance requirements**

| Minimum technical requirements items    | Category       |                  |                    | Required value             | Value                       |
|-----------------------------------------|----------------|------------------|--------------------|----------------------------|-----------------------------|
|                                         | Usage scenario | Test environment | Downlink or uplink |                            |                             |
| User experienced data rate              | eMBB-s         | Rural            | Uplink             | 100 kbit/s                 | -                           |
|                                         |                |                  | Downlink           | 1 Mbit/s                   | 1.2 Mbit/s                  |
| 5th percentile user spectral efficiency | eMBB-s         | Rural            | Uplink             | 0.003 bit/s/Hz             | -                           |
|                                         |                |                  | Downlink           | 0.03 bit/s/Hz              | 0.04 bit/s/Hz               |
| Average spectral efficiency             | eMBB-s         | Rural            | Uplink             | 0.1 bit/s/Hz               | -                           |
|                                         |                |                  | Downlink           | 0.5 bit/s/Hz               | 0.57 bit/s/Hz               |
| Area traffic capacity                   | eMBB-s         | Rural            | Uplink             | 1.5 kbit/s/km <sup>2</sup> | -                           |
|                                         |                |                  | Downlink           | 8 kbit/s/km <sup>2</sup>   | 12.1 kbit/s/km <sup>2</sup> |

Note eMBB-s is Enhanced Mobile Broadband-Satellite

## 2.3 Summary of use cases and services

The four main use cases envisaged for D2D are:

1. IoT for industry and automotive and utilities
2. Extending coverage to places not cost effective for TNs
3. Increasing availability and resilience for emergency services
4. Providing resilience during terrestrial network outages

Satellite backhaul is an adjacent use case which has synergies with satellite D2D. Such 'VSAT' systems have a converging technology ecosystem, and can address some of the D2D use cases, particularly when the devices are located indoors or onboard ships and aircrafts.

The new generation of 3GPP based satellite D2D networks are only just entering the early stages of rollout with limited coverage and capacity. We therefore consider how services will come online as the networks scale. For LEO satellites this means starting with discontinuous coverage and limited capacity. Table 2 identifies the service types, approximate user throughputs, and whether a continuous connection is required. For delay-tolerant services like messaging, anything is better than nothing. For delay-sensitive services like voice, it is better not to waste resources and frustrate users if the service is unusable.

**Table 2: Services and key requirements**

| Service         | Approximate User Tput, kbps | Continuous Connectivity |
|-----------------|-----------------------------|-------------------------|
| IoT & messaging | 1                           | not needed              |
| Voice           | 10                          | Yes                     |
| Basic data      | 100                         | desirable               |
| Broadband       | 1000                        | Yes                     |

All four services are applicable to all use cases, and are coming online as network capabilities permit. Table 3 notes the implication of each use case on traffic demand and the seamlessness of satellite-terrestrial integration.

**Table 3: Use case implications on network requirements**

| Use case                                          | Traffic Demand | Satellite terrestrial handover |
|---------------------------------------------------|----------------|--------------------------------|
| Coverage beyond TN                                | low            | Slow acceptable                |
| Availability & reliability for emergency services | low            | Seamless                       |
| Resilience for TN outage                          | Very high      | No TN                          |

Coverage extension implies locations that are not economically viable for terrestrial networks – or even a satellite backhauled access points, and thus presumed to have low traffic demand. Seamless integration of new with existing coverage is always preferable, but not essential, and users on the margins of terrestrial coverage are accustomed to intermittent connectivity. This is not the case where D2D should increase the availability and resiliency of working terrestrial connectivity for emergency services. Finally, TN outages create very high traffic demands which could overwhelm D2D capacity. This use case drives solutions such as critical user prioritisation and the ability to temporarily use of TN spectrum.

### 3. Spectrum availability and regulation

In this section, we assess the status and the spectrum for D2D services.

D2D satellite communications is being considered in both Mobile Satellite Service (MSS) and Mobile Service (MS) spectrum. A subset of MS spectrum is used by the MNOs in TNs to provide mobile services – often referred to as IMT spectrum.

#### 3.1 D2D in MSS bands

Currently, SNOs use spectrum allocated to MSS to provide D2D services, and are now considering their integration with mass market smartphone and IoT devices. 3GPP specifications standardised some of the MSS bands between 1467 to 2520 MHz for NTN operation. Hence this option entails mobile chipset vendors supporting the relevant MSS bands standardised by the 3GPP. Currently supported applications include voice, messaging, IoT and data services to smartphones, wearables and IoT devices. Compatibility and co-existence studies will generally have been conducted for existing MSS bands since these bands have already been allocated and planned for MSS services. Operating D2D services in the existing MSS bands does not require additional regulatory provisions, provided that the D2D services adhere to the regulatory requirements established by national regulators and the ITU under the MSS allocations. In most countries, operating D2D service can be authorised under the normal licence process.

To meet the growing demand for D2D services, additional allocation of MSS is considered for a number of spectrum bands under three WRC-27 Agenda Items (AI) as shown in

Table 4:

- AI 1.12 will consider opportunities for possible allocations of some spectrum bands to the low-data-rate Non-Geostationary Satellite Orbit (NGSO) MSS systems
- AI 1.13 will consider direct connectivity between space stations and IMT: Allocations to the MSS in the frequency bands between 694/698 MHz and 2.7 GHz to complement terrestrial IMT network coverage
- AI 1.14 will consider possible additional allocations to the MSS.

The results of WRC-27 will significantly influence future regulations regarding satellite-terrestrial integration.

#### 3.2 D2D in MS bands

The second variant of D2D service allows satellites to connect directly to existing mobile handsets using the frequency bands allocated for mobile service. The frequency bands considered by this variant are the bands that are identified for IMT by the ITU, which are used by terrestrial MNOs leveraging the existing mobile handsets and their associated chipset.

Since the International Telecommunication Union's (ITU) Radio Regulations (RRs) do not currently include any provisions for D2D-type services, there are no internationally agreed-upon rules on how spectrum should be managed for D2D services. According to the ITU RRs, any such service must operate on a 'non-interference, non-protection' basis under Article 4.4 of the Radio Regulations. Article 4.4 of the ITU Radio Regulations permits administrations to assign frequencies to stations without causing harmful interference to services operating in accordance with the Table of Frequency Allocations. This provision allows for flexibility in spectrum use, enabling countries to authorise transmissions outside the internationally agreed allocations, provided they do not interfere with other compliant services. Such stations must accept any

interference from services operating under the Table and are not entitled to protection. The satellite filing administration is responsible for addressing instances of interference.

In response to industry demand for D2D services, regulators in several countries have established regulatory frameworks to permit their operation. Notably, the UK and the USA have adopted two different approaches to facilitate access to spectrum for D2D services.

### **1. Authorisation of a subset of IMT spectrum bands for satellite D2D services in the UK:**

Ofcom [12] proposes a spectrum authorisation framework that provides an opportunity to use a subset of IMT bands below 3 GHz (i.e. 700, 700 SDL, 800, 900, 1400, 1800, 2100 and 2600 MHz bands, excluding Time Division Duplex (TDD) bands).

Ofcom proposes a variation to an MNO's existing licence and new exemption regulations that will enable mobile handsets and other SIM-enabled devices to lawfully connect to D2D services. The proposed process requires MNO to submit a request to Ofcom to modify the existing licenses for the bands proposed for D2D service use, using their spectrum. Further, any D2D service offering voice call capabilities will be required to take all necessary measures to provide uninterrupted access to emergency services as part of its voice communication offerings. Ofcom also proposed Power Flux Density (PFD) limits to minimise the risk of interference to adjacent channel mobile systems.

### **2. Modification of the Table of Frequency Allocations to authorise bi-directional, secondary MSS operations in certain spectrum bands in the US:**

The Federal Communications Commission (FCC) has adopted new rules effective May 2024 to facilitate supplemental coverage from space (SCS). These rules aim to enhance the reach of communications services, especially for emergency services in remote areas. The FCC also applies interim 911 call and text routing requirements for SCS operators. To allow satellite communications in certain frequency bands previously designated for terrestrial services, the FCC modifies the United States Table of Frequency Allocations to authorise bi-directional, secondary mobile-satellite service operations in certain spectrum bands that have no primary, non-flexible-use legacy incumbents. Currently authorised bands for SCS include 600, 700, 800, Broadband PCS, AWS-H Block<sup>2</sup>. To minimise interference, SCS authorisations are limited to six geographically independent areas, where terrestrial licensees must lease access to the spectrum to satellite operators.

Many other countries (e.g. Australia [13], New Zealand [14], Tanzania [15]) have published frameworks or regulatory guidance to support D2D satellite services. They are closely monitoring the global development of D2D technology and may undertake future regulatory work in this area if necessary.

D2D service operation in existing MSS bands depends on the spectrum bandwidth required for the existing incumbent services. Current MSS bands between 1467 and 2520 MHz have bandwidths that vary between 7 and 50.5 MHz. Further, some MSS bands are prioritised for safety-critical applications, meaning they will take precedence over all other mobile satellite service communications. For example, maritime mobile-satellite distress, urgency, and safety communications must have priority access and immediate availability over all other mobile satellite communications within a network operating in the mobile-satellite service. This includes frequency bands of 1,530-1,544 MHz, 1,626.5-1,645.5 MHz, 1,545-1,555 MHz, and 1,646.5-1,656.5 MHz.

---

<sup>2</sup> 600 MHz: 614-652/663-698 MHz, 700 MHz: 698-769/775-799 MHz, 800 MHz: 824-849/869-894 MHz, Broadband PCS: 1850-1915/1930-1995 MHz, AWS-H Block: 1915-1920/1995-2000 MHz

There are new frequency bands to be considered for MSS in Agenda items 1.12, 1.13 and 1.14 of WRC-27 (see

Table 4) [16].

Table 4: Overlap of the frequency bands considered under agenda items AI 1.12, 1.13 and 1.14

| Band          | AI 1.12<br>MSS for IoT | AI 1.13 D2IMT user Between<br>694/698 and 2700 MHz | AI 1.14<br>MSS |
|---------------|------------------------|----------------------------------------------------|----------------|
| 1427-1432 MHz | MSS↓                   | MSS↑                                               |                |
| 1880-1920 MHz | MSS↓↑                  | MSS↑                                               |                |
| 2010-2025 MHz | MSS↓↑                  | MSS↑                                               | MSS↑, R1 R3    |
| 2120-2160 MHz |                        | MSS↓                                               | MSS↓           |
| 2160-2170 MHz |                        | MSS↓                                               | MSS↓, R1 R3    |

WRC-27 AIs 1.12, 1.13 and 1.14 are helpful for terrestrial-satellite integration, in particular, the AI 1.13 direct satellite connectivity to IMT user between 694 and 2.7 GHz. The intention was to provide mobile services in remote areas and lower frequency bands.

In general, the selected spectrum in the AIs are portions of spectrum left over from other major allocations. In other words, gaps in the frequency range where the pattern does not fit together e.g. bottom 1800 band or that 1427-1432. These bands are often called the unpaired bands. Once these bands are accommodated around existing allocations, it may be possible to get new paired bands. There is also a mixture of earth-to-space and space-to-Earth applications considered in different AIs for different applications in the same region. e.g., on AI 1.12, 1427-1432 MHz is looking for MSS DL, and in AI1.13, the same band is looking for UL. Hence, it is on a future conference agenda. That would not work for the terminals or the satellites in practice. They are options and WRC will decide the best way forward.

### 3.3 Spectrum bands analysis

Figure 4 shows the main spectrum bands relevant to D2D services.

Table 4 3GPP NTN band definitions. Note:

- The top two rows. above the x-axis show 3GPP specified bands. The first row shows New Radio (NR)/ Evolved Universal Terrestrial Radio Access (E-UTRA) bands and the second row shows the NTN standardised bands. FDD pairs have the same colour.
- Bands below the x-axis show the ITU MSS allocations. The down arrow i.e. ↓ indicates the space-to-Earth direction and the up arrow i.e. ↑ indicates the Earth-to-space direction. It also indicated the geographic allocation i.e. WW indicates worldwide, R1 refers to Europe and Africa, R2 refers to the Americas, and R3 refers to Australasia.

The existing spectrum bands are mostly occupied, making it difficult to find new spectrum bands for new services and applications. The ability to share greatly depends on the incumbents in the band and adjacent bands. Further, new allocations require sharing studies to assess the feasibility of sharing with incumbents, if there are changes in parameters or usage compared to the existing studies.

Figure 4 shows that there is a mix of consistencies and inconsistencies i.e. paired and unpaired bands, in the frequency allocations between 1400-2600 MHz range. Inconsistencies appear due to historical decisions, driven by commercial requirements at the time.

For satellite terrestrial integration, one of the basic requirements is to have spectrum bands allocated to MSS. In 2 GHz, IMT band n1 (i.e. Up Link:1920 – 1979.7/Down Link: 2110.3 – 2169.7 MHz) is adjacent to MSS 2GHz band (i.e. 1980-2010 MHz (↑)/2170-2200 MHz (↓)). The 3GPP also standardised this band as n256. The allocations of these bands adjacent to each other at the ITU level was deliberate during the IMT-2000 development time. In the ITU, the industry envisaged a role for the satellite, specifically as the satellite component of IMT, and pressed to have either the band split between terrestrial and satellite or a satellite allocation alongside the terrestrial. During that time, the satellite component was recognised as part of the IMT-2000 along with the terrestrial components.

Currently, TNs operate in the 1800 MHz band (UL: 1710.1 -1785/DL:1805.1 – 1880 MHz), and Ofcom proposed this band for D2D. The figure shows that there is an obvious gap around 1800 MHz as there is no 3GPP standardisation of MSS allocation. Notably FCC's new rules for SCS allow D2D operation in the band n25 (i.e. UL: 1850–1915/DL:1930–1995 MHz). In addition, WRC-27 Agenda Items 1.12 and 1.13 consider the 40 MHz adjacent to the upper edge of the 1800 MHz DL i.e. 1880-1920 MHz. In the UK, under the proposed D2D framework, it would be possible for a TN User Equipment (UE) to connect to a satellite operating in the 1800 MHz band. However, under the Radio Regulations, there is no provision for a satellite operator to operate in that band since there is no MSS allocation. Regulatory provisions are necessary to promote satellite operation in parts of the 1800 MHz. Given that there is a big chunk of spectrum (i.e. 2x75 MHz of spectrum), there exists an opportunity for D2D service provision. However, without the provision in international regulations, SNOs are unlikely to include this band for satellite networks and obtain approval for frequency coordination.

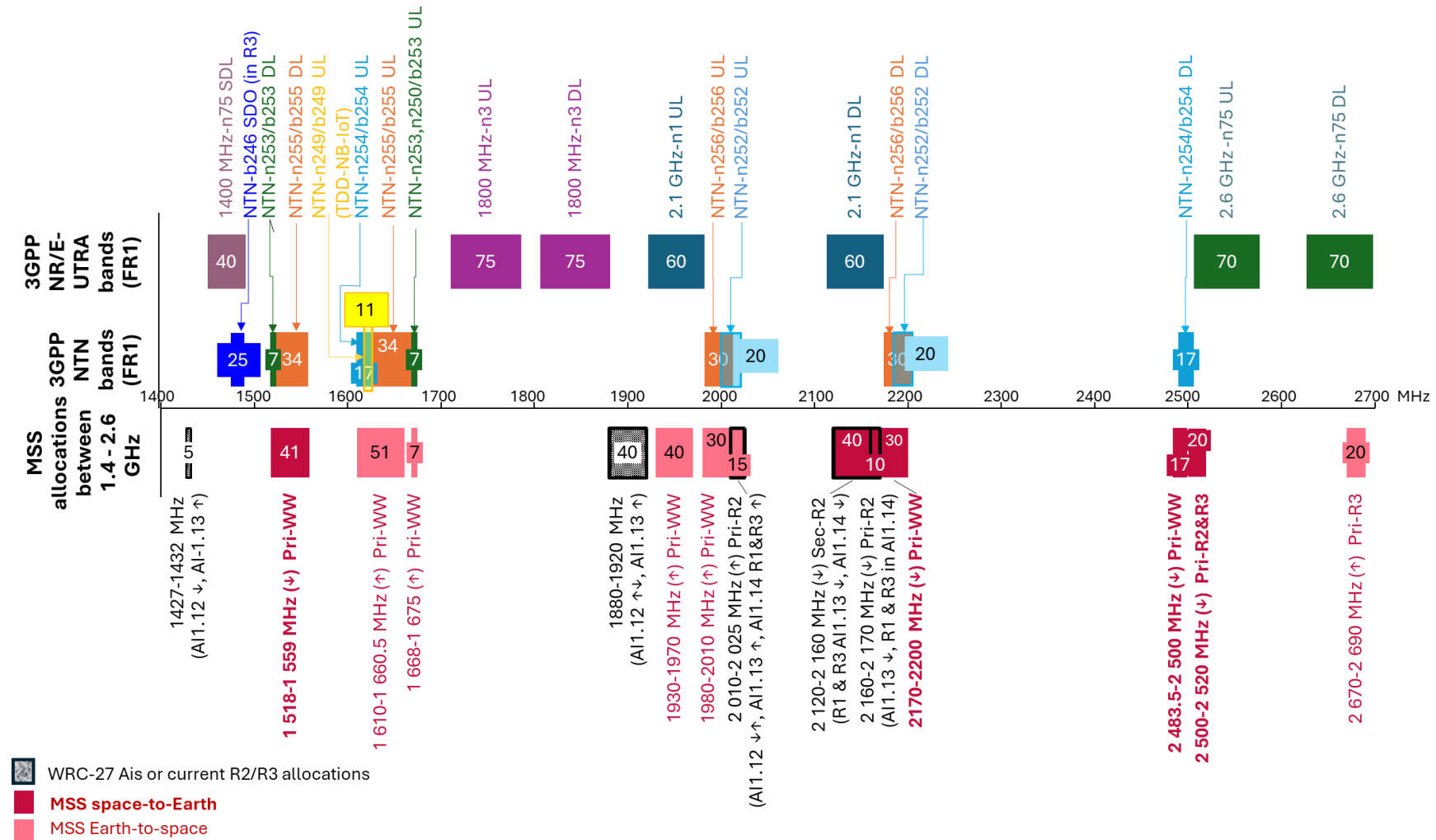
The satellite operation in the 1400 MHz band is not paired. Long round-trip delays in satellite connections make TDD challenging and so Frequency Division Duplex (FDD) is predominantly used. We note that IoT-NTN does though include a band specified for TDD operation.

If the 2600 MHz band is also allocated to MSS, there's an opportunity for MNOs to share the service provision responsibilities with the SNOs through a partnership since there is 2x70 MHz available. There is MSS allocation in 2483.5 to 2500 (R2 and R3 allocation up to 2520 MHz), which overlaps with NTN n254 DL. The NTN UL is 825 MHz away from the DL in 1610-1626.5 MHz, which is unusually far away in this case.

Although, there are MSS allocations above 14 GHz those bands are not suitable for D2D communications. These bands may be used for applications like backhaul connectivity.

Similarly, there are MSS bands in sub 1 GHz (e.g. from 137 to 614 MHz). However, they are not mainstream IMT bands and all of them have a bandwidth of less than 3 MHz except 608-614 MHz allocation in Region 2. Low bandwidth significantly restricts the data rates of D2D services. They may be viable for IoT-like applications, but not voice or broadband data and not suitable for public communications. Some of those bands are also used for military applications. Further, the use of the bands 137-138 MHz, 148-150.05 MHz, 399.9-400.05 MHz, 400.15-401 MHz, 454 456 MHz and 459-460 MHz by the mobile-satellite service is limited to non geostationary-satellite systems.

Figure 4: Relevant spectrum bands and their activities between 1400 GHz and 2600 GHz<sup>3</sup>

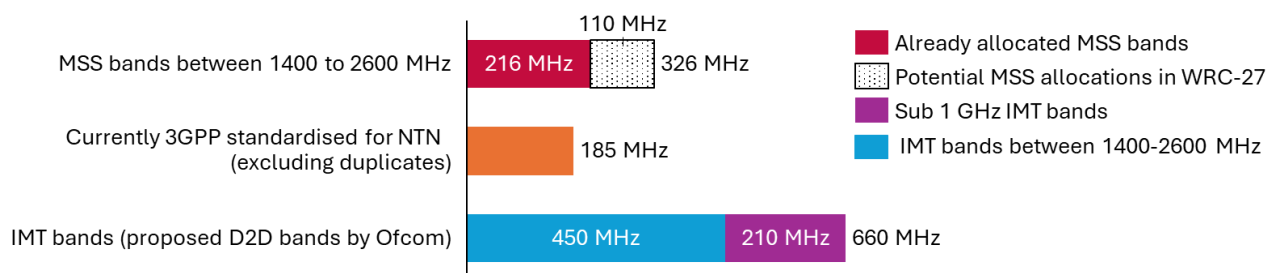


<sup>3</sup> The 3GPP NR/E-UTRA bands shown in the figure are a subset of all IMT bands within the specified range. We have selected the bands authorised by Ofcom for satellite D2D services in the UK.

Table 5: 3GPP NTN band definitions

|                                                                                          | NTN satellite operating band | UL (MHz)        | DL (MHz)      | Duplex mode        | ITU radio allocations                                                                       |
|------------------------------------------------------------------------------------------|------------------------------|-----------------|---------------|--------------------|---------------------------------------------------------------------------------------------|
| NTN satellite bands in between 1 GHz to 2.6 GHz (subset of FR1-NTN, 410 MHz – 14500 MHz) | n256/b256                    | 1980 – 2010     | 2170– 2200    | FDD                | MSS global                                                                                  |
|                                                                                          | n255/b255                    | 1626.5 – 1660.5 | 1525– 1559    | FDD                | MSS global                                                                                  |
|                                                                                          | n254/b254                    | 1610 – 1626.5   | 2483.5 – 2500 | FDD                | MSS global                                                                                  |
|                                                                                          | n253/b253                    | 1668 – 1675     | 1518– 1525    | FDD                | MSS global                                                                                  |
|                                                                                          | n252/b252                    | 2000 – 2020     | 2180 – 2200   | FDD                | MSS Global except 2010-2020 MHz<br>2010-2025 R2only (R1 & R3 consider in AI 1.14)           |
|                                                                                          | n251                         | 1626.5 – 1660.5 | 1518– 1559    | FDD                | MSS global                                                                                  |
|                                                                                          | n250                         | 1668 – 1675     | 1518– 1559    | FDD                | MSS global                                                                                  |
|                                                                                          | b249                         | 1616 –1626.5    | 1616–1626.5   | TDD                | MSS global                                                                                  |
|                                                                                          | n248                         | 14000 - 14500   | 10700– 12750  | FDD                | FSS<br>14-14.5 GHz Mobile-satellite<br>No MSS in 10.7-12.75 GHz                             |
|                                                                                          | n247                         | 13750 - 14000   | 10700– 12750  | FDD                | FSS but <b>no MSS</b>                                                                       |
|                                                                                          | b246                         | N/A             | 1467–1492     | Standalone DL Only | MOBILE, FIXED BROADCASTING SATELLITE<br><b>No MSS or FSS</b>                                |
| NTN satellite bands in FR2-(10700 MHz – 30000 MHz)                                       | n512                         | 27500 - 30000   | 17300 - 20200 | FDD                | FSS, Some MOBILE<br>19.7-20.1: <b>mss (R1)</b><br>20.1-20.2 <b>MSS</b>                      |
|                                                                                          | n511                         | 28350 - 30000   | 17300 - 20200 | FDD                | MOBILE, FIXED & FSS<br>29.5-29.9 GHz FSS, <b>mss (R1)</b><br>29.9-30 GHz <b>MSS and FSS</b> |
|                                                                                          | n510                         | 27500 - 28350   | 17300 - 20200 | FDD                |                                                                                             |
|                                                                                          | n509                         | 14000 - 14500   | 10700– 12750  | FDD                | FSS<br>14-14.5 GHz <b>mss</b><br>10.7-12.75 GHz <b>No MSS</b>                               |
|                                                                                          | n508                         | 13750 - 14000   | 10700– 12750  | FDD                |                                                                                             |

Figure 5 shows total spectrum allocations in Region 1 for MSS and 3GPP standardised for NTN.



**Figure 5: Total MSS allocations and NTN standardised bands**

Figure 5 shows that 3GPP standardisation is catching up with the MSS allocations in the 1.4 to 2.6 GHz range (i.e. 85% of the MSS allocated bands between 1.4 and 2.6 GHz are standardised within 3GPP for NTN operation), demonstrating that the industry is actively working to access spectrum, despite regional differences. A larger amount of spectrum available for MNOs for their TNs could pave the way for D2D operation within IMT bands, where there is spare capacity. However, this is subject to finding solutions to interference problems. The partnership between MNOs and SNO is important for this to happen.

### 3.4 Summary

Access to spectrum plays a key part in the D2D operation. There are two spectrum access approaches considered for next-generation satellite D2D operation:

1. D2D in MSS bands and D2D in IMT bands. While D2D operation in MSS bands can be authorised under the existing licensing process, the D2D ecosystem does not benefit from the mass market user base that the IMT community has. The MSS allocation at the ITU level implies that regulators would have made the necessary regulatory provisions by conducting the essential coexistence studies to ensure the smooth operation of Satellite D2D services.
2. D2D operations in IMT bands. This option requires further work by the regulators, and regulators in many countries, including the UK, are taking various initiatives to support this.

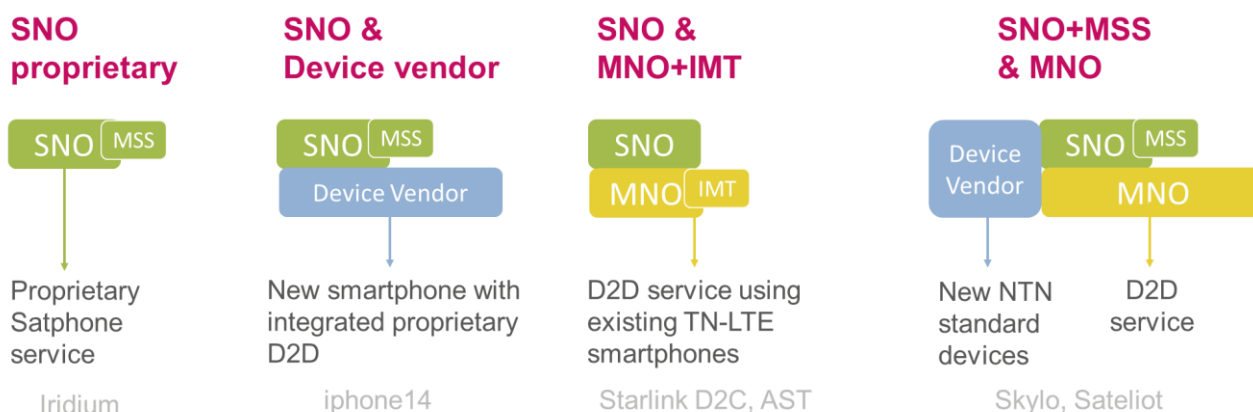
3GPP, in the meantime, standardised most of the MSS bands between 1.4 GHz and 2.6 GHz, providing chipset vendors with a signal to consider these bands in their roadmap. There is a mix of consistencies and inconsistencies, including paired and unpaired bands, in the frequency allocations relevant to D2D between 1.4 GHz and 2.6 GHz. Inconsistencies in pairing appear due to historical decisions driven by commercial requirements at the time.

MSS allocations above 14 GHz and below 1 GHz (e.g., from 137 to 614 MHz) are not suitable for a viable D2D business case due to various reasons.

## 4. Service providers and SNO partnership options to reach customers

Satellite network operators are providing a range of voice and data services directly to consumers and enterprise with satellite phones, IoT offerings and VSAT broadband. The next generational step for the satellite industry is the integration with the terrestrial telecoms ecosystem, particularly into smartphone user devices. The expectation is that integration will bring down the costs, allow satellite to address a much larger market, and thus fund build out of satellite network capacity.

In order to reach the consumer smartphone market, satellite network operators will need more complex partnership with the device ecosystem and terrestrial MNOs. We define four partnership models in Figure 6 below, which represent the past, present and future of satellite D2D. The partnership involves different parties bringing something to the table. The SNO brings the satellites, of course, but must make technology and spectrum choices in order to form partnerships with the device vendors and terrestrial operators. Terrestrial cellular networks are firmly rooted in the 3GPP ecosystem, which creates a market place of competing technology providers instead of bi-lateral arrangements with proprietary technologies. Whilst an ecosystem is preferable for a healthy diverse supply chain, it takes time to establish and is not agile, an important quality when develop new technology.



**Figure 6 SNO partnership options to address the D2D market**

These different partnership approaches are described below in the order they have and are being commercialised. The first partnerships enabling the fastest time to market, leveraging legacy assets and proprietary technologies. Later approaches promise greater scalability and economies of scale with the standards based ecosystem, but involve more parties to be aligned.

**SNO Proprietary, e.g. Iridium** We represent existing satphone services such as Iridium and Thuraya as SNO proprietary. A proprietary technology is defined for the constellation and Original Equipment Manufacturer (OEM) modem and device vendors build to specifications. Services operate in the SNO's MSS and FSS spectrum. The SNO runs the network, but retail is often outsourced to local or industry-specific service providers in the case of IoT. Service providers may re-sell SNO defined monthly plans, or may buy connectivity wholesale and repackage according to market connectivity requirements. For example, John Deere the agricultural vehicle supplier includes connectivity in their vehicles and have recently announced the inclusion of satellite in their connectivity [17]. One example use case is self-driving and optimised fertiliser dosing.

This proprietary approach works well in B2B markets and can be customised to address niches where benefits are high enough to justify the costs.

Satphones have low volume compared to smartphones and so cannot compete with R&D spend on smartphones for the quality of the user interface, cameras etc. Integration into smartphones is the next type of partnership.

#### **4.1 SNO partner with device vendor. e.g. Globalstar-Apple**

The first commercial direct to smartphone service was achieved by Globalstar's partnership with Apple by adding a proprietary Globalstar modem using L-band<sup>4</sup>) [18] to the iPhone14 to support emergency SOS and later messaging and location sharing services. Like the John Deere example, the service is bundled for product differentiation. Apple becomes the service provider, retailing Globalstar's capacity to consumers, with the first few years' connectivity built into the cost of product. Terrestrial MNOs did not need to be involved.

A similar solution based on Iridium's proprietary technology was developed by Qualcomm for the android ecosystem. Despite developing the technology, the partnership ended because smartphone vendors did not include the proprietary technology in their devices. Qualcomm said in a statement smartphone makers have "indicated a preference towards standards-based solutions" for satellite-to-phone connectivity. [19].

Iridium subsequently went on to drive 3GPP specification of a TDD mode for the IoT-NTN standard to work in their unpaired MSS L-band spectrum [20]. Similar partnerships were subsequently arranged between Skylo and Google for the Pixel 9 and 10 and with Samsung for their Galaxy S25, both based on the IoT-NTN standard, sometimes also referred to as Narrowband NTN (NB-NTN).

We see an evolving partnership between SNOs and device makers, initially with proprietary modems for existing constellations, but the smartphone ecosystems prefer standards and have driven SNOs to support 3GPP protocols on their constellations. This sets the scene for the technology to scale, but the issue of service provision and terrestrial integration remains a challenge for the SNO-Device vendor partnership alone.

Apple were already an established business-to-consumer (B2C) service provider, billing users for apps, cloud storage etc, so adding satellite to this portfolio is incremental. Usage-based billing has not been necessary so far – partly to encourage adoption and partly due to the limited capacity needed for the initial emergency messaging service. As the available performance improves, it may be necessary to regularly bill users on a consumption basis. Furthermore, for standards based D2D to scale, it needs to be included in the full gamut of devices from vendors who may not wish themselves to become service providers. This points to the need for SNOs to partner with MNOs to integrate satellite D2D in their service offerings and billing.

We also notice new partnerships are developing in the other regions. e.g. in China (1) BeiDou-3 Satellite System (GEO) partnership with China Mobile provides SMS services in MSS L and S-bands, and (2) Tiantong-1 Satellite System (GEO) partnership with China Telecom offers SMS, voice, and light data services in MSS S-band and in the Middle East Space42 (GEO) partnership Etisalat and Thuraya to offer Emergency SOS, SMS, Voice, light data services in L-band.

#### **4.2 SNO Partner with MNO sharing their IMT spectrum. e.g. Starlink-TMO US**

There are two flavours of SNO-MNO partnerships depending on whose spectrum is used, the SNOs MSS spectrum or the MNO's IMT spectrum. In the latter, satellites use terrestrial Long-Term Evolution (LTE) protocols in IMT spectrum supported by (the many compatible) existing smartphones that consumers already own. The key benefit is that the service can immediately work to extend the coverage of the MNO

---

<sup>4</sup> 1621.35 - 1626.5 MHz

networks without need to buy a new phone. There are caveats, but the basic premise works and is already commercially available with Starlink's direct-to-cell in ten partner MNOs<sup>5</sup> at the time of writing. [21]. A recent Youtube video demonstrates satellite data functionality in the TMO-US T-satellite data network with a range of apps including video streaming and video calling [22]. AST SpaceMobile and Lynk are rolling out similar technology, which we describe later in the technology section and compare with the 3GPP NTN standard features in sub 1 GHz spectrum bands.

Starlink claim "Direct to Cell works with every LTE phone wherever you can see the sky" [23], but there appear to be some limitations on which devices support data services, although it is not clear whether this a technical or regulatory approval barrier [24].

Surety of spectrum access is essential for operators to invest in network infrastructure deployment. The IMT spectrum used has some risk attached which must be shared between SNO, MNO and national regulators. The use of satellite over IMT spectrum is new and was unforeseen when rules for these bands were defined. National regulators have made provisions to allow services to be switched on, mostly on a no interference, no protection basis, as detailed earlier in the spectrum section. Partners will have an expectation on the associated limits to utility of the spectrum, in terms of the powers, locations and directions of transmissions in those bands, but there carries some risk that these are overestimated.

The use of the TN-LTE protocol for D2D differs from 3GPP NTN approach which introduced new signalling to share complexity between UE and satellites. The TN approach is agile, but much of the network implementation falls outside of the scrutiny of the standards process. This expedites implementation and rollout, at the cost of supply chain resilience. Markets are more resilient when there are multiple providers for all required aspects. We note that in Sep25, SpaceX and their MNO partners Telstra, TMO-US, KDDI along with Qualcomm, Mediatek and Apple all supported a proposal to add the three MNO's IMT bands to the NR-NTN specifications [25]. The proposal was not agreed at that meeting, but may return, and nevertheless demonstrates an intention to migrate IMT band D2D to NR-NTN standard protocols., presumably once Rel17 NR-NTN devices become available.

IMT D2D providers Starlink and AST have both recently acquired MSS spectrum from Echostar [26] and Ligado, respectively. This affords a greater degree of spectrum sovereignty, giving them a stronger negotiating position in forming MNOs partnerships.

### **4.3 SNO with MSS spectrum partners with MNO**

In this partnership, the SNO brings an end-to-end D2D network operating in their MSS spectrum. The MNO brings access to their existing customer base which already has complementary capacity and indoor coverage from their terrestrial network as well as that of their international roaming partners. There are strong synergies here to make for a win-win partnership.

Smartphones supporting MSS bands started coming onto the market in 2025 with the Samsung Galaxy S25 and Google Pixel 10 [27]. Satellite services for these phones are currently available via the skylo-verizon partnership. [28][29]. Note that these two smartphone models are also being touted as compatible with Starlink – T-mobile's IMT based TN-LTE Direct to Cell [30][31].

---

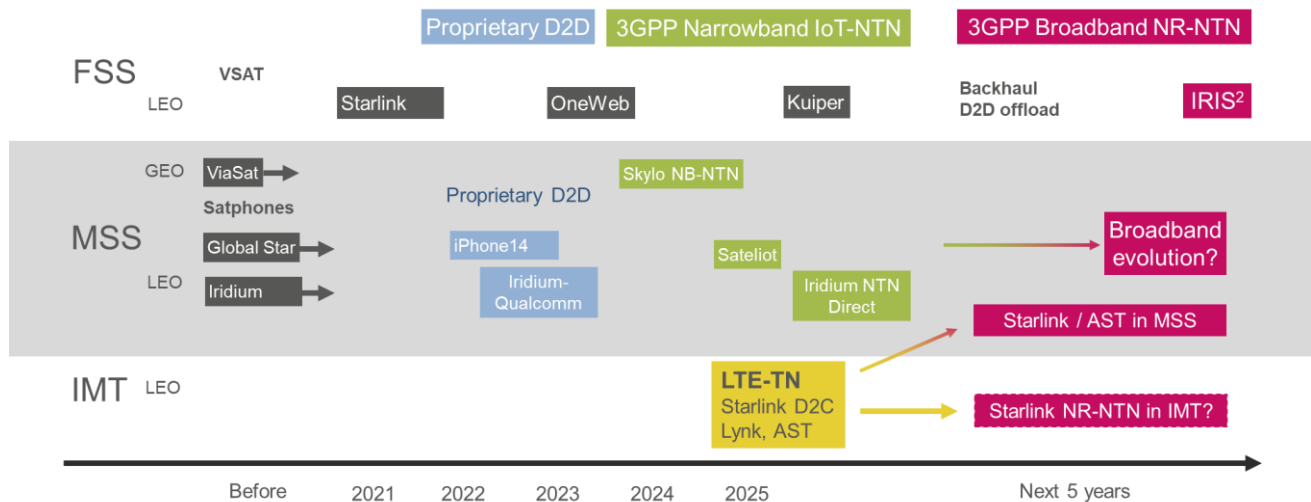
<sup>5</sup> E.g. 2x5 of 1900 MHz in US with T-Mobile and 2x5MHz of 1800MHz in Switzerland with Salt Mobile

#### 4.4 Summary

Considering recent commercial events in for satellite D2D, we have identified four ways SNOs are partnering with MNOs to provide D2D services and integrate them with the terrestrial smartphone ecosystem.

- SNO proprietary in MSS
- SNO + device vendor in MSS
- SNO + MNO using IMT spectrum
- SNO using MSS + MNO

**Figure 10** shows a timeline summary of the different D2D commercial offers based on these partnerships, which also includes the air interface protocols used. Events have proven that technology matters, with markets expressing a preference for standards-based solutions over proprietary ones. The figure also includes the VSAT/backhaul solutions using FSS spectrum which are an adjacent use case with a converging technology ecosystem.



**Figure 7 Timeline of commercial D2D services, their spectrum and technologies**

D2D has arguably been available for years in the form of the satphones prior to the current interest in terrestrial smartphone integration. The first integration was with Globalstar's modem into the iPhone 14. A similar solution for Android based on Iridium gained no traction with the market's preference for standards. This prompted Iridium to drive specification work in 3GPP for a TDD mode of the Narrowband IoT-NTN standard for the Iridium NTN direct service. Skylo and Satellite launched their own IoT-NTN services which also operates in MSS. In the meantime, direct to TN-LTE services were being launched by Lynk and Starlink, the latter claiming ten MNO partnerships with more to follow. AST Spacemobile are also trialling a similar direct to TN-LTE approach with their MNO partners.

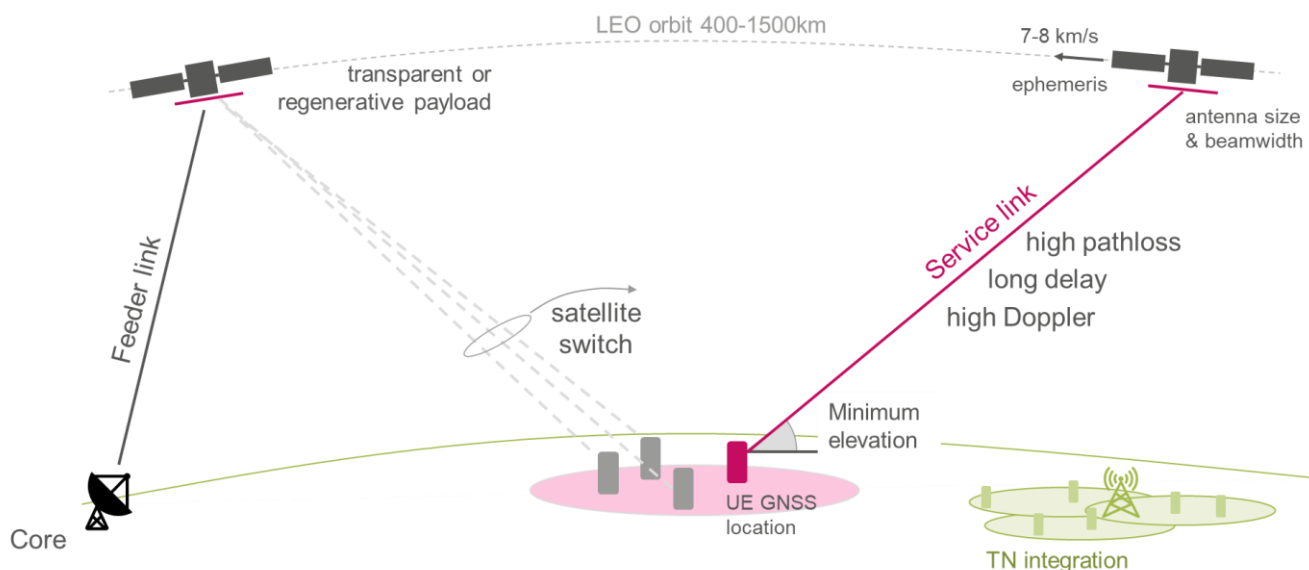
Next, we will see MSS based IoT-NTN and IMT based LTE-TN approaches scale with more satellites and more MNO partnerships. SpaceX and their partners have indicated the intention to eventually migrate their IMT services to NR-NTN standards. They have also now acquired their own MSS spectrum, and it would seem likely they'll need to adopt a 3GPP NTN standard for device compatibility. SpaceX recently indicated a 2-year timeframe before devices start shipping supporting their band [32].

So far NR-NTN has had little mention for D2D, but Eutelsat and Mediatek have trialled it and state it will be a key feature of the IRIS<sup>2</sup> constellation in FSS around the end of the decade [33].

Further, current trials and partnerships leading early deployments have primarily utilised the existing MSS L/S band spectrum, as well as MNO spectrum ranging from 1.4 to 2.6 GHz and sub-1 GHz MSS spectrum, to provide IoT-like services.

## 5. Technology standards roadmaps

### 5.1 Technical challenges of Satellite D2D and how they are solved



**Figure 8: Key technical challenges of satellite D2D**

There are many good summaries of 3GPP NTN technology available e.g. 3GPP [34], IEEE comms [35], NTN Book [36], so here we pick out key aspects which highlight the challenges and solutions of different D2D approaches – NTN and Direct to TN UEs, as well as TN interworking.

#### 5.1.1 Access link in NTN and for direct to TN UEs

The principal challenge D2D is using 3GPP protocols over the satellite-UE access link. Link ranges are over 1000km (even for 600km orbits) which means high path losses and much longer round-trip delays than 3GPP TN was designed for. LEO satellites move at around 27,000 km/h, creating Doppler shifts orders of magnitude higher than 200km/h considered high speed in terrestrial networks.

Two key features introduced into the NTN standards in Rel17 mitigate the high Doppler and the large delays as follows. Delay and Doppler on the downlink do not prevent the UE detecting and synchronising and decoding transmissions, since it has no particular frame of reference in frequency or time to consider before it connects. However, in order to transmit on the uplink and become connected, the UE must ensure its transmission will be on frequency and on time when it arrives at the satellite. Terrestrial networks protocols design in margin to accommodate the initially unknown round trip delay and Doppler. The margin represents an inefficiency, but this is engineered to be a small overhead. In 3GPP NTN, satellites include their time evolving ephemeris in their broadcast information (System Information Block 19 or “SIB19”), which the UE combines with its GNSS location in order to pre-compensate the frequency and timing of

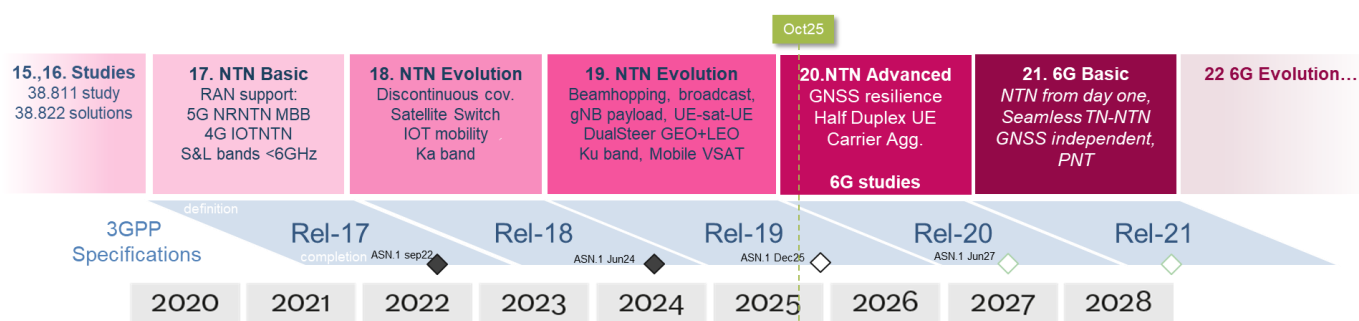
uplink transmissions so that they all arrive on time and on frequency. This does require UEs to maintain an accurate GNSS location, which is discussed later under ‘GNSS resilience’

The direct to unmodified TN UE systems demonstrate it is possible to make the access link work without the ephemeris and UE GNSS location. Instead of the UE pre-compensating its transmission, the satellite post-compensates the received signals from different UEs across the cell based on the known cell centre of the satellite beam. In order to make this work, the satellite must create very narrow beams which limit the *range* of Doppler and timing error for UEs across the cell to that experienced in terrestrial networks. Narrow beams implies large array apertures, and also more beams (and beam processing) to cover a given area on the ground. Processing requires space and power if on the payload, or feeder link capacity if on the ground. So this approach represents a higher cost for the satellite operator. As we will show later in the performance analysis, cell densification through smaller beams and more satellites is the main way to increase satellite network capacity as demand grows. Thus such large arrays may anyway be needed even with NTN standards at some point.

Proponents of Rel17 NTN – argue that that these NTN features agreed by the ecosystem in 3GPP represent a more equitable sharing of cost, complexity and risk between SNOs and UE chipset providers. A small amount of processing in each UE significantly reduces the cost of the space segment.

### 5.1.2 3GPP NTN roadmap

NTN standardisation in Rel-17 extends beyond the fundamentals of access link timing and frequency compensation. Additional timing relationships are specified which model delays of the access and feeder link to provide the ‘hooks and eyes’ for other features such as scheduling and Hybrid Automatic Repeat reQuest (HARQ). Consideration is given for feeder-link switch over and satellite switch in LEO constellations. Cells in NGSO scenarios may be quasi-fixed (for the duration of a satellite flyover) or earth moving. Rel17 provided the basic feature set for NTN, which has been enhanced with various features and additional frequency bands as shown in **Figure 9**. We have described how the Direct to TN UEs systems solve the doppler and timing issues, but the NTN roadmap reveals many other challenges in NTNs which benefit from specification enhancements. We describe some of these below



**Figure 9: 3GPP NTN release roadmap: features and timing of standards and productisation**

## 5.2 Handovers and LEO Satellite switching

‘Mobility’ 3GPP terminology refers to changes of cell rather than just movement of the UE. Idle mode mobility is called cell reselection, where UEs autonomously change the cell it ‘camps on’. Many cells are combined together into larger tracking areas. The core network keeps track of which tracking area the UEs are in, and can ‘page’ over all cells in that area if it needs the UE to connect, e.g. to receive an incoming call. If cell reselection results in the UE joining a new tracking area, it must connect in order to perform a

tracking area update. For NTN tracking areas represent fixed geographical areas, even when cells are earth moving. Cells can belong to multiple tracking areas allowing overlap to avoid frequent updates for UEs moving along boundaries.

Handover specifically refers to changes of cell in connected mode. It occurs due to UE movement as in terrestrial cellular networks, and also due to the movement satellites in NGSO constellations. NTN standards enhance the existing Conditional Handover (CHO) feature, which provides conditions to UEs for evaluation to decide when to handover. CHO is enhanced to support NTN scenarios by adding time and location-based triggers. These are more appropriate in LEO satellite networks than signal strength based due to LOS propagation and predictable timing of when UEs change cell or must switch from departing satellite to an arriving one. The time-based trigger allows the network to manage the timing of individual UEs within a group needing to change. Cell broadcast information in NTN's SIB19 can include its neighbour satellite's ephemeris to expedite cell changes.

Satellite switching with resync is a further Rel-18 enhancement that streamlines these frequent changes of serving satellite which avoids layer 3 radio signalling. Random Access Channel-less (RACH-less) handovers are also included in time-based CHO in Rel18. Reducing or avoiding the need for signalling improves spectral efficiency but can also improve robustness of procedures.

### 5.3 NTN-TN Integration

Three reference architectures have been defined in 3GPP which broadly define different options for Terrestrial-satellite integration, shown in **Figure 10**, with the coverage of the two networks shown above.

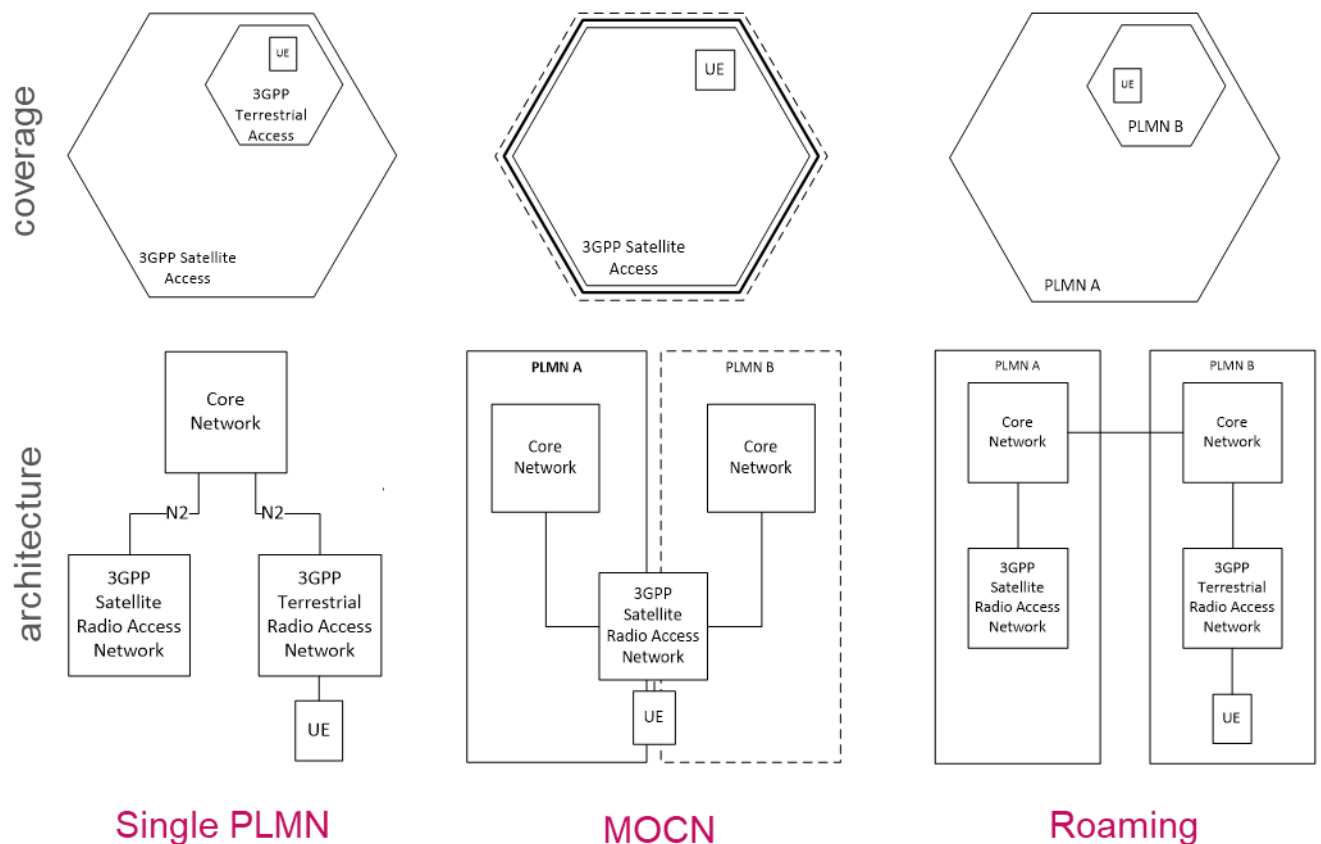


Figure 10: NTN-TN integration scenarios [TR 23.737]

### 5.3.1 Single PLMN

Single Public Land Mobile Network (PLMN) is the most tightly integrated scenario, with a single core network controlling both TN and NTN RANs within the same PLMN. The UE can handover between TN and NTN base stations using the N2 interface, potentially within the same Access and Mobility Function (AMF). This is potentially how the Direct to TN UE approaches (albeit for LTE and Evolved Packet Core or EPC) where the satellites appear to UEs as normal base stations in the same network.

UEs change between TN and NTN using the mobility processes described above. In particular, there are a number of measurement events which can be used to trigger handover, listed below. B1 and B2 are used to trigger inter-Radio Access Technology (RAT) handovers potentially TN and NTN.

Measurement events defined for 5G NR [37]

- A1 serving becomes better than threshold
- A2 serving becomes worse than threshold
- A3 neighbour becomes offset better than Serving Cell
- A4 neighbour becomes better than threshold
- A5 Serving Cell becomes worse than threshold1 and neighbour becomes better than threshold2
- A6 neighbour becomes offset better than Serving Cell
- B1 inter RAT neighbour becomes better than threshold
- B2 Cell becomes worse than threshold1 and inter RAT neighbour becomes better than threshold 2

RAN-based Dual connectivity has been proposed for terrestrial-satellite integration with a common core, and whilst not precluded, some experts [36] consider it to be impractical given the difference in size of NTN cells with TN cells and the requirement to tightly co-ordinate resource over an X2 interface.

Additionally core-based multi-connectivity is considered precluded in the satellite access study in 23.737 [38] *“The satellite access is considered as a 3GPP access in Service and System Aspects Working Group 2 (SA WG2), a single registered UE cannot simultaneously establish multiple Packet Data Unit (PDU) sessions via different 3GPP RATs. Therefore, the multiple PDU sessions scenario described in KI #7 will not occur, and no solutions are needed.”*. An ambitious work item started out in Rel18 to specify dual connectivity for a range of TN-NTN scenarios as well as private public networks. The scope of the subsequent work was significantly eroded by down scoping to remove scenarios involving 'splitting' of traffic across two connections. Disagreement over this led to a rare technical vote at 3GPP plenary SP#101, which did not achieve sufficient consensus to proceed. This reveals significant opposition in 3GPP to the multi-connectivity scenarios which would make it easier to users to switch between networks.

### 5.3.2 Multiple Operator Core Networks (MOCN)

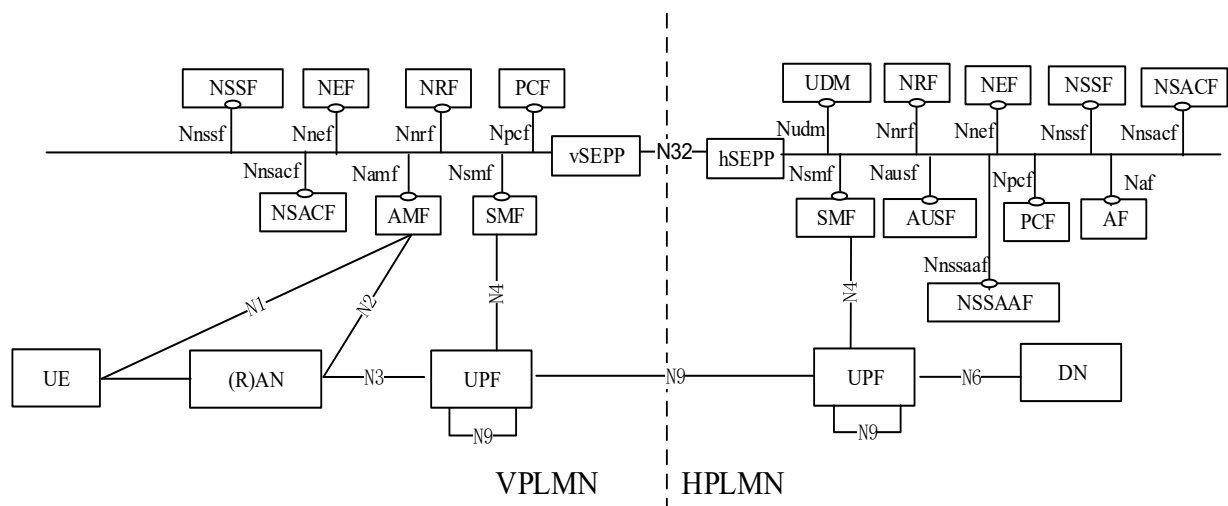
The Multiple Operator Core Networks (MOCN) approach is a form of neutral hosting in that the satellite network is shared between multiple core networks. In this case, the shared satellite Radio Access Network broadcasts system information for both PLMNs whose core networks are available. These PLMNs may also be with different Mobile Country Codes (MCCs). Country agnostic codes exist (90x) and have been already used for satellite networks, e.g. Iridium 90105.

### 5.3.3 Roaming

The third option is Roaming, where TN and NTN are roaming partners with their own core networks and separate PLMNs. This seems an appropriate approach for LEO SNOs operating in MSS wishing to partner with many MNOs in different regions. Roaming is widely used already and as we know, authentication and charging are tried and tested.

The UE attaches to the visited PLMN (VPLMN) and their traffic may break out in the visited network (called Local Breakout) as shown in **Figure 11**, or Home Routed. The NTN will be the visited network for consumers with a (terrestrial) MNO subscription. User traffic flows between the UE over the RAN to the User Plane Function (UPF) and onto the Data Network (DN) typically the public internet. Home routing means the user traffic is routed through the visited network to a UPF in the home network before it can be connected to an external data network. Note that home routing is not a prerequisite for Lawful Intercept<sup>6</sup> (LI), and in fact a Europol paper claims it makes LI harder [39].

Charging is initiated by the sessions management function (SMF) in the home and visited networks, which interact with their associated Charging Function (CHF). The Visited-CHF (or V-CHF) generates call detail records (CDRs) for the inbound roaming traffic, and correspondingly the Home-CHF generates CDRs for the outbound roaming traffic. [40],[41]. These CDRs are then processed and rated against a customers service plan in order to produce an itemised billing statement.



**Figure 11: Roaming 5G System Architecture, Home Routed [42]**

## 5.4 Other Notable NTN Enhancements in 3GPP

### 5.4.1 GNSS resilience Rel20 - GNSS still needed, but keeps working in temporary outage

The newly agreed Rel20 scope for NTNs include a study on GNSS resilient operation [43]. NTN UEs currently rely on an accurate GNSS location in order to transmit on the correct frequency and timing on the uplink. The UE must not transmit if GNSS location is not available. Note that 3GPP timing is derived from GNSS location, not GNSS timing. The study considers how NR-NTN could continue to operate during short GNSS

<sup>6</sup> Lawful Intercept is a term that describes the interception and monitoring of network subscriber traffic by authorized agencies for law-enforcement purposes.

outages, potentially using a broadcast cell centre location for an approximate position, combined with Random Access Channel (RACH) to resolve residual timing error. Among the long list of 6G proposals is GNSS-Free operation and also a Positioning, Navigation and Timing (PNT) feature. (There are several proposals for GNSS free operation being considered and one of these are likely to be adopted in an update of the standard)

#### 5.4.2 TDD mode for IoT NTN

Following the lack of take-up of the Qualcomm-Iridium proprietary D2D approach similar to Apple/Globalstar, Iridium drove a work item in 3GPP to enable a TDD mode for IoT-NTN [44] in their 1616-1626.5 MHz MSS band. Work was declared complete in Sep25 with the addition of the band into IoT NTN UE spec 36.102 [45].

#### 5.4.3 IMS voice calls over GSO for NB-IoT-NTN, and ultra low rate Codec

A recently agreed Rel20 study [46] which may also apply to NGSO - considers a number of enhancements such as semi-persistent scheduling, RRC connection setup, UE transmit power higher than PC1, etc. A related task in System Aspects Working Group 4 (SA4) is the creation of an ultra-low bitrate codec [47] which can operate at rates of 1-5kbps.

#### 5.4.4 Low Selection PLMN rules to avoid D2D overload

A short work item was agreed [48] for SA1 to add a new operator controlled Lower Selection-priority PLMN list to preventing undesirable TN UEs to connect to and overload a D2D satellite network.

#### 5.4.5 6G NTN

3GPP is currently studying solutions for 6G in release 20, ahead of normative work on a 6G specification in release 21 with a technology proposal available for the ITU-2030 submission in Mar2029 and specifications mid 2030. NTN was very popular in a 3GPP's 6G workshop in March 2025 with around two thirds of the 240 presentations mentioning NTN and requesting it from "day one". The workshop summary [49] captured "Seamlessly integrating terrestrial and non-terrestrial networks (NTN) for ubiquitous coverage and resilient services." and a "Harmonized TN and NTN design".

Detail on 6G NTN has yet to be agreed. One initial proposal supported by several members of the NTN community [50] proposed a long list of features (see Table 6):

**Table 6: List of initial NTN capabilities for the proposed 6G RAT, prioritised by the NTN community for the RAN to study.**

| Proposal 1: as part of the Rel-20:              | Proposal 2: as part of the Rel-21 or beyond:           |
|-------------------------------------------------|--------------------------------------------------------|
| NTN resiliency to GNSS service                  | Quasi seamless TN/NTN mobility in connected mode       |
| PAPR requirements for NTN downlink transmission | 6G NTN coexistence with IoT-NTN or NR-NTN in same beam |
| Flexible frame structure                        | Multi connectivity/carrier aggregation                 |
| Extended coverage                               | Positioning Navigation and Timing                      |
| Flexible duplex mode support at UE level        | Enhanced network verified UE location service          |

|                                                     |                                                              |
|-----------------------------------------------------|--------------------------------------------------------------|
| Support of High Definition (HD)-FDD at Network side | RAT energy consumption determination for one-to-many service |
| Mitigate specific NTN Propagation impairments       | MIMO via several satellites                                  |
| Operation at low error rate                         |                                                              |
| Massive messaging capability                        |                                                              |
| Extension of satellite foot print                   |                                                              |
| Positioning Navigation and Timing                   |                                                              |
| Enhanced network verified UE location service       |                                                              |

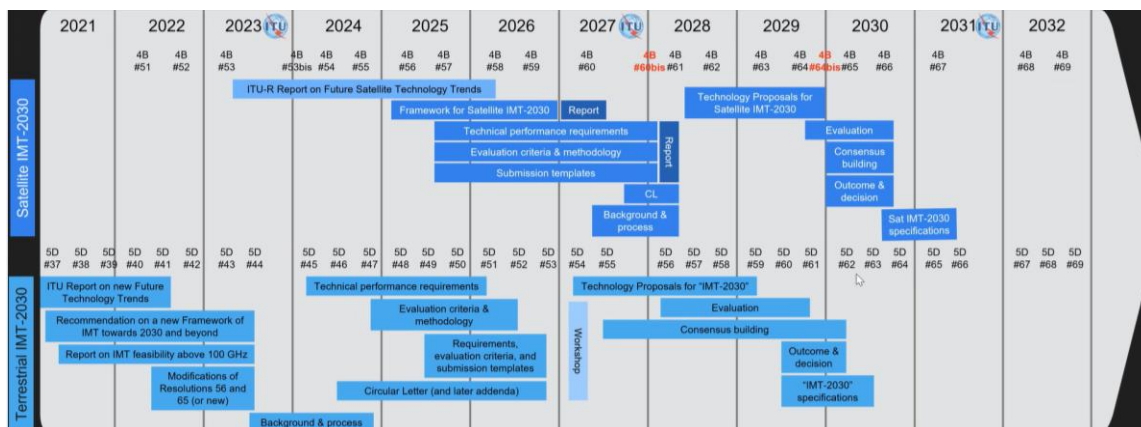
## 5.5 IMT2020 Satellite and IMT2030

The evolution of standards and the integration of NTN into the 3GPP is now significantly enhancing the role of satellites in the 5G and 6G ecosystems.

The integration of satellite technology within the framework of the IMT-2020 system was provided in the ITU-R M.2514 report [51]. This document outlines the vision, requirements, and evaluation guidelines necessary for developing satellite radio interfaces that support IMT-2020 standards. Additionally, the 3GPP TR 37.911 [52] study provides insights into the self-evaluation process for the submission of satellite radio technology within the IMT-2020 context. Recommendations like ITU-R M.1182-1 [53] emphasise the critical importance of harmonising terrestrial and satellite mobile communication systems, highlighting ongoing efforts to enhance connectivity and service quality across diverse environments.

WP 4B has developed a work plan, timeline, process and required deliverables for the future development of satellite IMT. The development of the Background on the satellite component of IMT-2030 was started in October 2025 and is expected to be completed in April 2027 within WP4B.

Figure 12 shows the satellite and terrestrial components of IMT-2030 work plan. IMT-2030 satellite component developments are trying to align with its terrestrial counterpart so that the once the requirements are released and candidate RATs are evaluated, both can be evaluated as a single candidate technology rather than two separate candidate technologies. This will further enhance the integration of satellite and terrestrial IMT technologies in the future.



**Figure 12: satellite and terrestrial components of IMT-2030 work plan**

## 6. Devices and chipset considerations

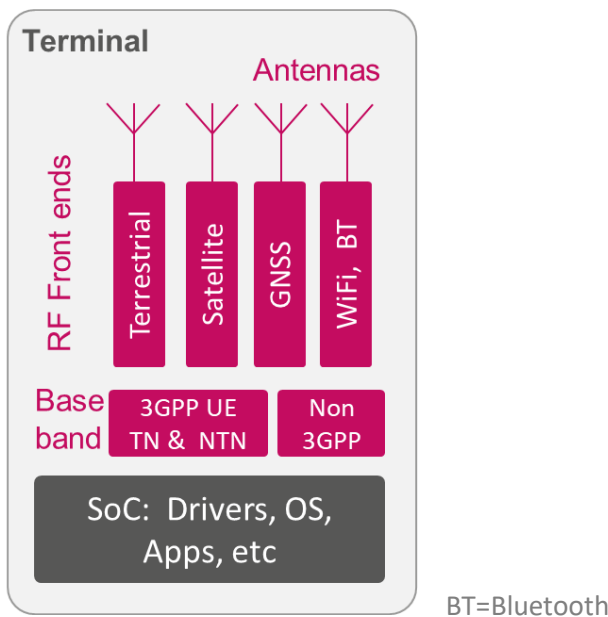
### 6.1 Chipsets underpin the smartphone ecosystem

The smartphone is the foundation of the cellular ecosystem, and making them affordable for the majority of the world’s population has been a result of globally applicable standards. Over time, the standards for cellular voice have evolved to incorporate services previously requiring dedicated technologies, such as paging, Private Mobile Radio (PMR), IoT Television, and now satellite comms.

Whilst there may be hundreds if not thousands cellular device vendors, the majority of these rely on a handful of chipset vendors to provide the underlying functionality. The global scale of the chipset market enables chipset vendors to sell highly sophisticated chipsets at low prices by amortising significant R&D cost over the large shipment volumes. The downside of this scale is that markets must work with ‘off the shelf’ chips designed for the most common cases. And whilst standards specifications ostensibly reflect the market’s requirements with a set of features and frequency bands, not all standardised features get implemented into chipsets. Standards are defined years in advance of commercial productisation and represent a broad menu of implementation options. What’s in and what’s out is then decided by UE chipset vendors considering factors such as network support, spectrum availability, Return on Investment (RoI) of Research and Development (R&D) vs increased sales volumes and/or pricing, cannibalisation of other product lines, competitive strengths and weaknesses, etc.

It is important to view integration of satellite communications into smartphones from the perspective of the smartphone chipset makers, as they are a principle enabler of the device based ecosystem.

### 6.2 Key elements of the Smartphone chipset



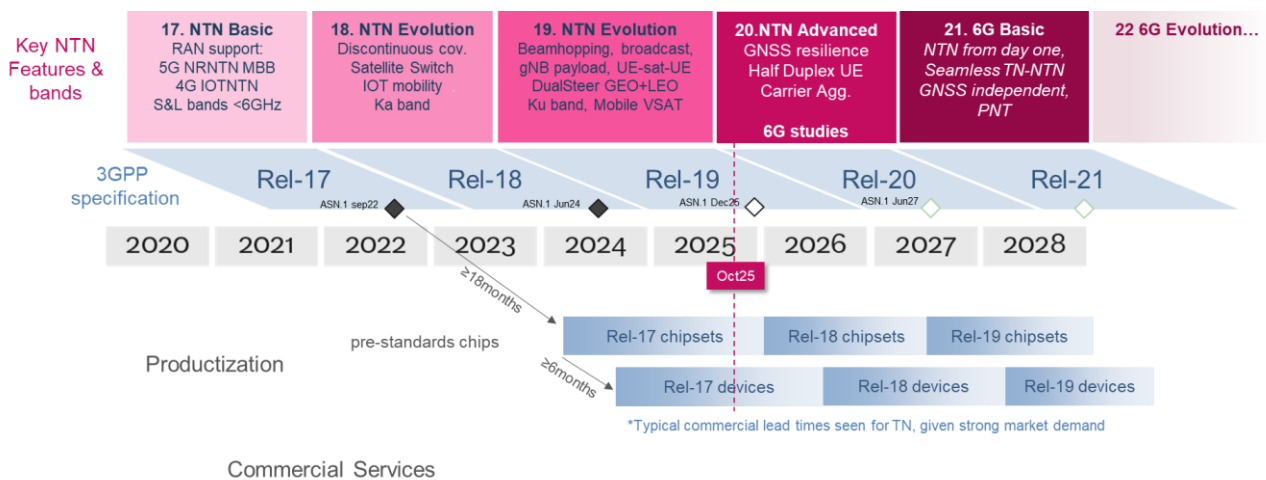
**Figure 13 Model of main chipset elements in smartphones relating to wireless communications**

A chipset comprises a number of chips which work together. Figure 13 shows the main components involved in the communication aspects of interest in this study. Other aspects are left out. To achieve the desired price point for smartphones it is anticipated that it is required to produce a System on a Chip (SoC) with a Central Processing Unit (CPU), memory and various hardware accelerators to support the myriad of smartphone functions – operating system, apps, hardware drivers etc.

Wireless communications comprise basebands - which define the air interface and associated protocol stack - and the RF front ends and antennas which determine the supported frequency bands and duplexing modes FDD, TDD and Half Duplex (HD)-FDD. Smartphones include both 3GPP's 2G-5G basebands as well as non 3GPP including Wi-Fi, Bluetooth (BT) and GNSS. The first satellite-smartphone integration also used non-3GPP basebands. Apple's iPhone 14 included a Qualcomm X65 modem for the Globalstar satellite network [54].

The IoT-NTN baseband is establishing a viable ecosystem of devices and networks in addition to Iridium's above. Skylo use Viasat's GSO satellites to operate their IoT NTN service, and to provide a long list of certified devices [55] including Samsung's Galaxy S25 and Google Pixel 9 and 10.

### 6.3 Timing of 3GPP NTN chipset and devices availability



**Figure 14: Timing of 3GPP NTN chipset devices availability**

Chipsets are on the critical path for commercialisation and depend on the freezing of the Abstract Syntax Notation.1 (ASN.1) Code for each 3GPP release. It takes around 18 months between ASN.1 freeze and first available chipsets, and then another 6 months before these are integrated into devices.

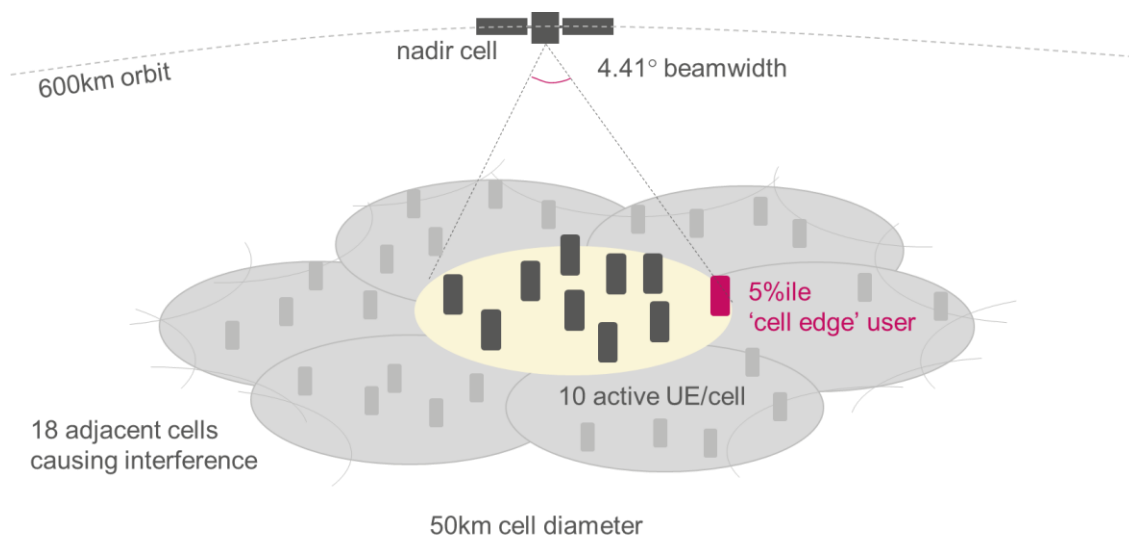
At the time of writing, Rel-19 is approaching the key ASN.1 freeze date in December 2025. ASN.1 is a form of code which captures the agreed protocol structure and information elements to support the new release features. Its freezing allows chipset vendors to proceed with silicon implementations. For 3GPP chipsets there has typically been an 18 month lead time for chipset availability, and an additional 6 months before devices using these chips are available. However, implementing features has a cost and so only those features perceived to have a market will be implemented. Chipset vendors may also promote pre-standards chips in areas where market leadership may be strategically important. Mediatek was promoting a Rel17 NTN chipset early in 2023., and later claimed a world first NR-NTN over LEO connection, with a test chipset [56]. In Oct 25, Nordic semiconductor and Sateliot claimed a world first Rel-17 standard IoT connection over a LEO satellite, likely to be IoT-NTN [57]

## 7. Performance analysis and spectrum requirements

Here we consider the user throughputs and cell capacities expected from D2D networks which like terrestrial cellular networks are a product of the spectral bandwidth, spectral efficiency and cell density. We consider the performance available from 3GPP baseline assumptions and how these parameters may be varied to increase capacity for given spectrum, or reduce the spectrum needed for given performance.

### 7.1 User and Cell Spectral efficiency and throughput

As part of the IMT-2020-satellite evaluation process, 3GPP members developed and aligned RF network simulations of satellite D2D based on the Rel-17 NR-NTN specifications. The process is detailed and rigorous and the results are useful benchmark for expected performance. The process intends to test the limit of specifications and so does not necessarily represent the first commercial implementations. 3GPP meeting ITU-R's requirements is a foregone conclusion – the real outcome of the process is to see what configuration is needed to be assumed to meet requirements. 3GPP capture their analysis in TR37.911 [58] *"Study on self-evaluation towards the IMT-2020 submission of the 3GPP Satellite Radio Interface Technology"*. Satellite deployment scenarios are based on the NTN study item from TR 38.821 [59]

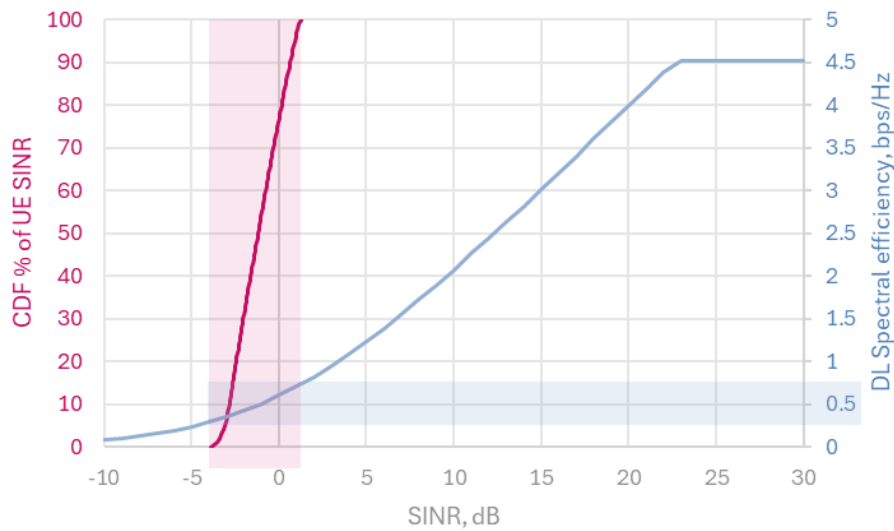


**Figure 15: Model assumed for performance analysis**

Figure 15 illustrates how D2D performance is modelled, similar to the method used for terrestrial networks. 19 cells are simulated with many UEs randomly scattered across the area covered. An instant is modelled where each cell is transmitting and receiving with ten active UEs. Uplink and downlink link budgets are evaluated to derive each UEs coupling loss, its 'Geometry' SINR and in turn the spectral efficiency (SE) it would achieve with a 3GPP modem. Each cell's bandwidth is then shared between users according to its spectral efficiency. A proportional fair scheduler is assumed which allocates a larger share of resources to users with lower SE, which increases the worst-case user throughput at the expense of others as well as cell capacity. To avoid edge effects, results are only used for the UEs in the central cell of the network. The simulation is repeated many times with different random UE locations to build up a sample for statistical analysis.

**Figure 16** shows the downlink UE SINR distributions for a calibration simulation with frequency reuse of 1. SINR is generally low – with around 75% having negative SINR. The variation between best and worst UEs with D2D is much less than would be seen in terrestrial networks, where UEs close to the base station could achieve high SINRs of 20 dB or more. A SINR to spectral efficiency curve is overlaid which indicates that UE

SEs would be in the range 0.3~0.8 bit/s/Hz in this scenario, firmly in the Quadrature Phase Shift Keying (QPSK) range, as can be seen from the MCS index tables in 3GPP specification 38.214 [60].



**Figure 16: Downlink Geometry SINR distribution in NR-NTN cell and SNIR to Spectral efficiency**

**Table 7** provides a range of metrics from the 3GPP analysis, and converts them into cell and user throughputs. The ‘average’ spectral efficiencies given represent the cell average efficiency and cell throughput. For a baseline 5+5 MHz channel bandwidth, there would be 2.9 Mbps for downlink and 0.7 Mbps for uplink. Given there are 10 active UEs in a cell, average user throughput is simply a tenth of the cell’s, so 286 kbps DL and 73 kbps for UL. It is interesting to note that the equivalent TN requirement for rural eMBB is 3.3 and 1.6 bit/s/Hz/TRxP for downlink and uplink, respectively. The average spectrum efficiency for rural TN is therefore expected to be 6.6x higher than D2D for downlink and 16x higher for uplink, if the IMT2020 requirements are assumed to be representative. IMT spectrum used for D2D will be less efficient than in a rural base station.

**Table 7: NR-NTN Cell and user spectral efficiencies and throughputs in 5+5 and 30+30 MHz channels**

| NR-NTN Performance metric       | Cell Average |       | Average user |        | 5%-ile 'cell edge' user |       |
|---------------------------------|--------------|-------|--------------|--------|-------------------------|-------|
|                                 | DL           | UL    | DL           | UL     | DL                      | UL    |
| Spectral Efficiency, bit/s/Hz   | 0.572        | 0.145 | 0.0572       | 0.0145 | 0.031                   | 0.006 |
| kbps throughput in 5+5 MHz BW   | 2860         | 725   | 286          | 72.5   | 155                     | 30    |
| kbps throughput in 30+30 MHz BW | 17160        | 4350  | 1716         | 435    | 930                     | 180   |

The 5<sup>th</sup> percentile user throughput represents a worst case or cell edge UE. Counter-intuitively, the cited spectral efficiency represents that user’s throughput relative to the *cell* bandwidth rather than the spectral resources scheduled to that user. It is done this way to factor the benefit of fair scheduling – cell edge users will get more than one tenth of the cell’s bandwidth. As such, we cannot compare the 5%ile user SE with the SINR to SE conversion shown in **Figure 16**.

The key result in **Table 7** is the 5% ile user throughput of 155 kbps for downlink and 30 kbps for uplink achievable with a 5+5 MHz paired FDD spectrum allocation. 155/30 kbps for DL/UL is sufficient for a voice service, with the lowest rate codecs working down to around 6kbps. These data rates would also support a basic data service – web browsing is usable at these rates.

3GPP also provides a user experienced data rate analysis based on 30+30MHz spectrum allocation, a subset of results is shown in **Table 8**. Results do not scale exactly from cell edge spectral efficiencies as they are

averaged over a different set of contributing companies. For the Frequency Reuse Factor (FRF) of 1 and 2 UE antenna case used above, the rates are 0.91 Mbps in downlink and 0.15 kbps uplink – close to 6x the 5+5 MHz .

The IMT-2020 satellite guidelines include a requirement that the bandwidth must be “At least up to and including 30 MHz”. A new 3GPP work item was created in Rel18 [61] to add support for this bandwidth, interpreted as 30MHz each for downlink and uplink. And this bandwidth was used in calculations of data rates and area capacity, detailed below.

**Table 8 3GPP 5%-ile User Experienced Data Rates, 30+30 MHz channel, with scintillation loss. [62]**

| Direction | Frequency reuse factor | ITU Requirement (Mbit/s) | DL user experienced data rate (Mbit/s) |
|-----------|------------------------|--------------------------|----------------------------------------|
| Downlink  | FRF = 1                | 1                        | 0.91                                   |
|           | FRF = 3                | 1                        | 1.12                                   |
| Uplink    | FRF = 1                | 0.1                      | 0.15                                   |
|           | FRF = 3                | 0.1                      | 0.28                                   |

## 7.2 Area traffic capacity

Area traffic capacity is the cell throughput divided by the cell area, or as ITU-R define [51]:

$$\text{area traffic capacity, } C_{\text{area}} = \rho \times W \times SE_{\text{avg}}$$

Where W is channel bandwidth,  $SE_{\text{avg}}$  is average spectral efficiency.  $\rho$  is defined as Transmission Reception point (TRxP) or site density (TRxP/m<sup>2</sup>), a TN concept. For NTN a TRxP is a satellite which can support many cells at different locations, so seems that  $\rho$  represent cell density, i.e. 1/cell area.

The 50 km diameter beam footprint has a hexagonal cell area of 1624 km<sup>2</sup>. Cell capacities with 30 MHz channels over this area were 17.1/4.4 Mbps for DL/UL, yielding area capacities of 12/3 kbps/km<sup>2</sup> for DL/UL as shown in Table 9.

**Table 9 Area traffic analysis (2UE antennas, with scintillation loss) [37.911]**

| Direction | Frequency reuse factor | ITU Rural eMBB-s requirement (kbit/s/km2) | DL area traffic capacity (kbit/s/km <sup>2</sup> ) |
|-----------|------------------------|-------------------------------------------|----------------------------------------------------|
| Downlink  | FRF = 1                | 8                                         | 12.07                                              |
|           | FRF = 3                | 8                                         | 11.30                                              |
| Uplink    | FRF = 1                | 1.5                                       | 3.06                                               |
|           | FRF = 3                | 1.5                                       | 4.19                                               |

The earlier user throughput analysis assumed 10 active UEs in the 1624 km<sup>2</sup> cell – so an active user density of 1UE every 162 km<sup>2</sup>, i.e. 0.006 users per km<sup>2</sup>. An Office for National Statistics [63] definition of rural is an area having less than 150 inhabitants per km<sup>2</sup>, so the ratio of active:total users would need to be of order 1:24000.

ITU-R M.2514-0 does not provide a justification of the area traffic requirement. We note that for TN requirements from ITU-R M.2410-0, the area traffic requirement is given only for the indoor hotspot and is 10Mbit/s/meter<sup>2</sup> - a factor of 1.25 x 10<sup>9</sup> greater than for NTN, so is not a useful comparison.

## 7.3 Increasing area capacity

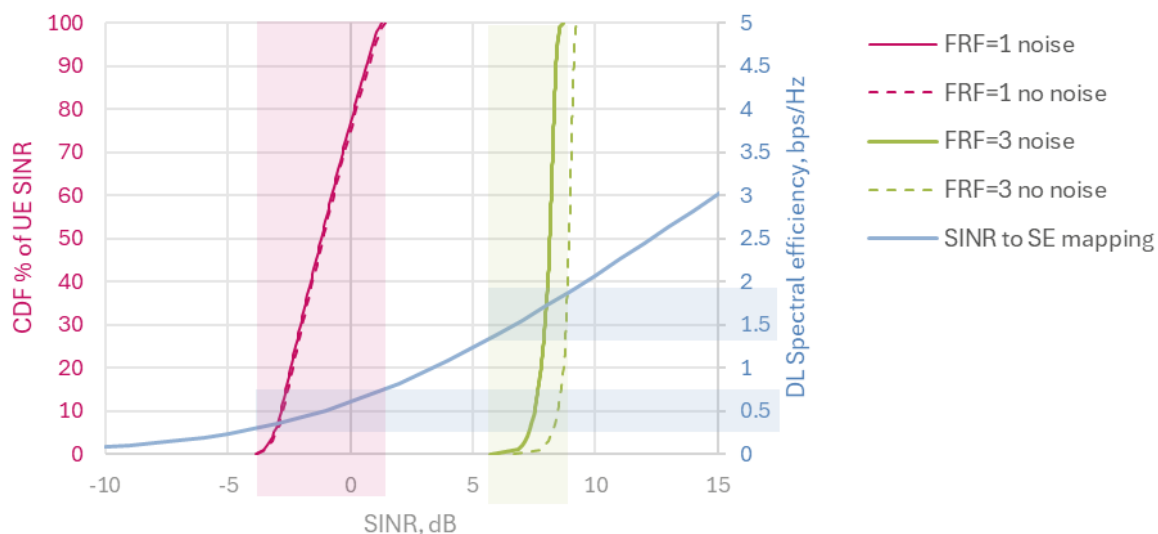
The area traffic capacity equation above indicates the three contributing factors: Channel bandwidth, spectral efficiency and cell density i.e. 1/cell area . We discuss below how each these might flex in order to achieve a viable D2D service.

### 7.3.1 Channel bandwidth

Downlink + Uplink channel bandwidths of 30+30 MHz were needed to meet the ITU's 8 kbps/km<sup>2</sup> area traffic requirement and the 1 Mbps user experienced data rate. For instance, in Europe, 2x15 MHz of the 2 GHz MSS band was originally acquired by Inmarsat (now Viasat) and EchoStar (in the process of selling to Starlink). With 2x15 MHz per operator, the product of cell density and spectral efficiency would need to double to continue to meet the ITU requirements per network. Having two networks with half the spectrum each should amount to the same overall capacity, but the maximum UE throughput on any one network would be halved.

### 7.3.2 Spectral efficiency

3GPP's analysis includes several geometry SINR calibration curves shown in **Figure 17** which indicate potential for increasing spectral efficiency. Results presented thus far are for Frequency Reuse Factor of one (FRF=1), where each cell re-uses the full channel bandwidth. An alternative to this is FRF=3 where only a third of the spectrum is used in each cell. A re-use pattern then avoids the need to use the same spectrum in neighbouring cells thus reducing interference, improving SINR and spectral efficiency. However, the available bandwidth per cell is reduced by 1/3 which counteracts the SE gain. The blue shading in **Figure 17** indicates the range of SE in both cases, and FRF=3 has approximately 3x the SE of FRF=1. The net effect of frequency reuse would be neutral. **Table 9** showed that FRF=3 gave slightly lower DL capacity but higher UL capacity, although variations could be due to different contributing companies rather than fundamentals.

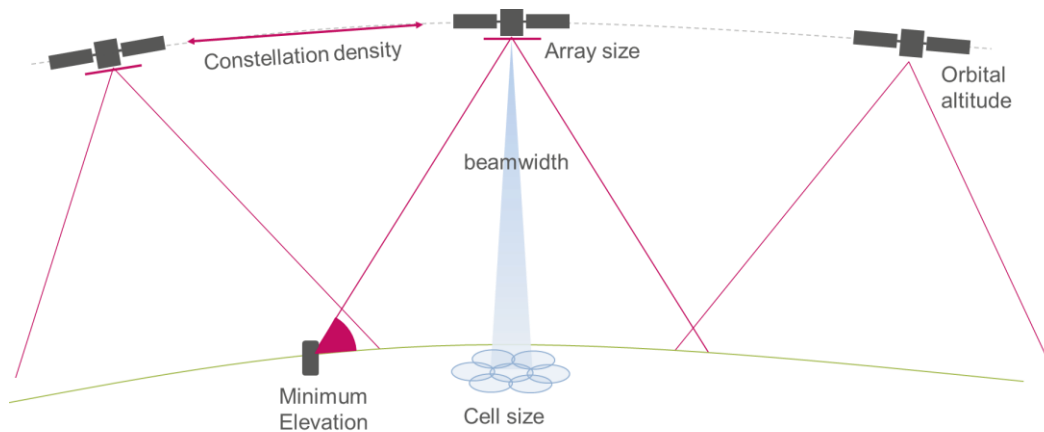


**Figure 17: Potential spectral efficiency improvement with frequency reuse and/or higher EIRP**

A further insight can be taken from the noise and no noise results shown in **Figure 17**, which are assumed to mean that the no noise curves are in fact the signal/interference ratio. In the FRF=3 case, removal of noise improves SINR by around 1dB, indicating potential to improve SINR though higher transmit power. This is not the case on the FRF=1 curve, indicating that network capacity is limited only by interference from adjacent beams and increasing EIRP would have no benefit to capacity. Spectral efficiency improvements might therefore be achieved through interference reduction – beam shaping, for example, or some form of cancellation.

### 7.3.3 Cell density

Factors impacting cell density are shown in **Figure 18**. 3GPP's analysis assumed a 2 m satellite antenna at 2 GHz producing a nadir beamwidth of 4.3 degrees, which at an altitude of 600 km creates a 50 km diameter cell. The satellite's coverage area is defined by the minimum elevation angle that a connected UE would ever see. Within this coverage area, the satellite's array antenna produces many beams, each supporting one cell. In theory area capacity is limited by cell density, but this assumes that the satellite itself has the sufficient power and processing to load. In practice payload power space and weight are all expensive resources to be optimised. The satellite operator will also trade-off individual satellite capacity versus the number of satellites in an orbital plane.



**Figure 18: Satellite constellation factors impacting cell density**

A further constraint in the direct to unmodified LTE devices is that cell sizes must be small enough to limit the range of Doppler and timing advance experienced by UEs. Whilst the satellite can compensate for Doppler and timing advance at the cell centre, the variation for UEs at the edge of the beam must be within the limits for terrestrial UEs. These smaller beams do though increase cell densities and thus area capacity as shown in **Table 10**. Starlink are currently deploying a dense constellation of smaller ~2.5 m antenna satellites, whereas AST have fewer larger satellites at a higher orbit. Their relative cell densities can be applied to 3GPP's analysis to derive an increase in area capacity at the assumed 30 MHz - or a reduction in the spectrum required for the same performance. These parameters are likely to evolve over time, but are included here to represent the current range of cell densities possible with different orbits and antenna array sizes.

**Table 10 Example D2D satellites and their cell density relative to 3GPP's NR-NTN baseline**

|                           | NR-NTN | Starlink D2C | AST Spacemobile |
|---------------------------|--------|--------------|-----------------|
| Frequency, GHz            | 2      | 2            | 2               |
| Antenna diameter          | 2      | 2.5          | 8               |
| beamwidth 30deg scan, deg | 4.3    | 3.4          | 1.1             |
| orbit, km                 | 600    | 350          | 700             |
| cell diameter, km         | 45     | 21           | 13              |
| relative cell density     | 1x     | 5x           | 12x             |

3GPP's self-assessment considered the performance in beam at the nadir – on satellite boresight. Performance off boresight for cells nearer the minimum elevation angle of 30 degs will likely be less due to reduced directivity and elongated cells. At these angles, Ericsson [64] suggest the achievable throughput might be reduced by a factor of 2. Starlink's denser constellation with closely spaced satellites may reduce the occurrence of such high scan angle connections and achieve greater spectral efficiency and cell density.

## 7.4 Summary of performance

3GPP analysed their NR NTN and IOT NTN specifications to demonstrate how the requirements set by the ITU for the IMT-2020 satellite candidate technology can be met.

3GPP analysis was for a best-case D2D scenario with a satellite directly overhead. One source thought performance would be half at low elevations, so we may imagine the average case is 0.75x. With a 5+5 MHz spectrum, the 5%ile cell edge user (in a cell of 10UEs) achieves 155/30 kbps for DL/UL, sufficient for voice and a basic data service. In a worst-case cell with half these rates, voice is still achievable. 30+30 MHz was needed to meet ITU's satellite rural EMBB requirements for throughput and area capacity. Again, in a worst-case cell, then we should double this required bandwidth for NR-NTN.

## 8. Conclusions

### 8.1 Main conclusions of the study

Satellite network operators are providing a range of voice and data services directly to consumers and enterprise with satellite phones, IoT offerings and VSAT broadband. The next generational step for the satellite industry is integration with the terrestrial telecoms ecosystem, particularly into smartphone user devices. The expectation is that integration will bring down the costs, allow satellite to address a much larger market, and thus fund extensive build out of satellite network capacity.

#### End customer use cases and service level expectations

A number of market drivers and technology enablers have motivated this generalisation step. LEO satellite constellations have become more affordable for operators due to reductions in launch costs, thanks to reusable launch vehicle technology. At the same time, broadcast TV has been a mainstay of the satellite industry income but is now diminishing as consumers shift to on-demand unicast streaming over broadband networks. The industry views telecoms as their next market, and the support of direct to smartphone voice and data is a key market segment.

Four use cases are envisaged for satellite D2D:

- Extending coverage to places that are not cost effective for TNs
- Increasing availability and resilience for emergency services
- Providing resilience during terrestrial network outages
- IoT for industry and automotive

Satellite backhaul is an adjacent use case which has synergies with satellite D2D. Such 'VSAT' systems have a converging technology ecosystem, and can address some of the D2D use cases, particularly when the devices are indoors on onboard. D2D can also act as a demand discovery service – identifying remote locations with sufficient demand to justify investment in terrestrial infrastructure.

#### Performance analysis and spectrum requirements

For the D2D use cases we identified, we have proposed quality of service expectations for the main services of IoT/messaging, voice and data. For delay tolerant IoT and messaging, anything is better than nothing and users will still benefit even with single digit kbps provide acceptable user throughputs. For delay sensitive services like voice and video calling, and interactive data services, it is better not to waste resources and frustrate users if the service is unusable. An ultralow rate voice codec is being specified to

work at 1-5kbps, but 10's kbps is preferable and coverage must be continuous. Basic mobile data is acceptable with 100s kbps downlink, and less on the uplink, whilst broadband would suggest at least 1Mbps DL. 3GPP's assessment of their NR-NTN D2D technology for the ITU's IMT2020s informs channel bandwidths and cell densities needed to meet minimum service level requirements. With 5+5 MHz spectrum the 5%ile cell edge user (in a cell of 10UEs) a performance of 155/30 kbps for DL/UL is achieved and is sufficient for voice and a basic data service.

Area capacity will depend on the size of the cell over which these ten active UEs are served. 3GPP's baseline assumption is for a 45km diameter cell, and this needs 30+30MHz of spectrum to meet the ITU's rural satellite area capacity requirement of 8kbps/km<sup>2</sup>. The same capacity and user throughputs could be achieved with less spectrum and a higher cell density. Higher cell density implies smaller beam footprints for satellites, achieved with larger antenna arrays and/or lower orbits. We observe that Starlink D2C currently has a cell density around 5x the 3GPP baseline, and AST Spacemobile around 12x. Thus if all else was equal, Starlink could meet the IMT2020-sat requirements with 5+5MHz channels, whilst in this bandwidth AST would have double the throughput and capacity. Configurations will evolve and these figures will change.

We should caveat these findings as the 3GPP analysis was for a best-case cell of satellite directly overhead, with indications that a worst case may have around half the performance. Also, the direct to TN-LTE UEs in IMT spectrum currently used by Starlink and AST may not be as spectrally efficient as 3GPP's NR-NTN standard which includes a number of enhancements and optimisations on top of the terrestrial NR protocol.

IMT2020 average spectral efficiency requirements for terrestrial rural eMBB are 6.6x higher than D2D for downlink and 16x higher for uplink. If we assume the requirements are present

### **Device and Chipset Support**

Early D2D approaches were based on proprietary constellation specific air interface protocols. Apple's integrated a proprietary Globalstar modem into the iPhone14 to support its emergency SOS and location sharing D2D services. However a similar proprietary technology offer from Iridium and Qualcomm was not adopted by Android device makers, with Qualcomm citing that market's preference for standards based approaches. Terrestrial cellular networks are firmly rooted in the 3GPP ecosystem, which creates a market place of competing technology providers instead of bi-lateral arrangements with proprietary technologies. Whilst an ecosystem is preferable for a healthy diverse supply chain, it takes time to establish and is not agile, an important quality when developing new technology.

With their IMT based approach SpaceX and Lynk are able to connect to existing TN-LTE and thus can immediately address a large market with no impact device and chipset vendors. However it places all the complexity onto the implementation of the space segment, which presents risk and cost for satellite operators. NTN standards represent an agreed sharing of complexity between network and UEs and may be more sustainable in the long run. SpaceX and partners have proposed adopting NR-NTN protocols in their IMT bands. And both SpaceX and AST have now acquired MSS spectrum, and it would seem likely that only a standards based D2D approach will be acceptable for smartphone chipset and device vendors.

### **Spectrum Implications**

Industry is actively working to access spectrum, despite regional differences. This is evident from the fact that about 85% of the MSS allocated bands between 1.4 and 2.6 GHz are standardised within 3GPP for NTN

operation. D2D operation in IMT bands will require regulatory provisions at the international level, but this could pave the way for D2D operation where there is spare capacity, provided solutions are found to interference problems. The partnership between MNOs and SNO is crucial for this to happen. Considering the amount of spectrum available for MSS and IMT, finding 30+30 MHz per operator would be significantly challenging. This will lead to compromises on performance or high-cost satellite systems to achieve the expected data rates from D2D systems.

## **8.2 Recommendations for future work**

We recommend the following activities for future work:

- Based on the identified use cases and their service requirements, a detailed simulation exercise to determine the spectrum requirements, focusing on applications relevant to D2D communication, would be helpful. Currently, compatibility and co-existence studies are underway in preparation for the WRC-27 Agenda Items 1.12, 1.13, and 1.14. The detailed spectrum requirement simulations will complement these ongoing studies. The spectrum requirements are directly linked to the service throughput levels, spectral efficiency, including the frequency reuse factor, and the cell density, which also depends on the size of the antenna on the satellite. Since the D2D ecosystem is currently evolving, it would be beneficial to consider a range of plausible scenarios based on the real-world parameters to identify the spectrum requirements. As technology evolved, it would be useful to gather typical end-user throughput levels achieved in practice to validate the simulations and performance simulations.
- Developing a harmonised regulatory approach and regulatory guidance for D2D satellite services is essential to encourage innovation and minimise the consequences of market dominance. This is particularly important when considering the spectrum of the operation for D2D services.

## Appendix A Abbreviations

| Abbreviation | Expansion                                                                  |
|--------------|----------------------------------------------------------------------------|
| 3GPP         | Third Generation Partnership Project                                       |
| 5GAA         | 5G Automotive Association                                                  |
| AI           | Artificial Intelligence                                                    |
| AMF          | Access and Mobility Management Function (in 5G core network)               |
| ASN.1        | Abstract Syntax Notation One                                               |
| B2C          | Business-to-Consumer                                                       |
| BT           | Bluetooth                                                                  |
| CDF          | Charging Data Function (in 5G core network)                                |
| CHF          | Charging Function (in 5G core network)                                     |
| CHO          | Conditional Handover (in cellular networks)                                |
| CPU          | Central Processing Unit                                                    |
| D2C          | Direct-to-Consumer                                                         |
| D2D          | Device-to-Device                                                           |
| DL           | Downlink                                                                   |
| DN           | Data Network                                                               |
| eMBB-s       | enhanced Mobile Broadband - satellite (often used in the context of NTN)   |
| EPC          | Evolved Packet Core (LTE core network)                                     |
| ESA          | European Space Agency (or Earth Station Antenna, depending on context)     |
| ESN          | Emergency Communications Network                                           |
| E-UTRA       | Evolved Universal Terrestrial Radio Access (LTE's radio access technology) |
| FCC          | Federal Communications Commission (US regulatory body)                     |
| FDD          | Frequency Division Duplex                                                  |
| FR1/2        | Frequency Range 1 / Frequency Range 2 (for 5G NR)                          |
| FRF          | Frequency Reuse Factor                                                     |
| FSS          | Fixed-Satellite Service                                                    |
| GNSS         | Global Navigation Satellite System                                         |
| HAPs         | High Altitude Platform Stations                                            |

|        |                                                         |
|--------|---------------------------------------------------------|
| HARQ   | Hybrid Automatic Repeat reQuest                         |
| HD     | High Definition/Half Duplex                             |
| IMT    | International Mobile Telecommunications                 |
| IoT    | Internet of Things                                      |
| ITU    | International Telecommunication Union                   |
| JU     | Joint Undertaking                                       |
| LEO    | Low Earth Orbit (satellite)                             |
| LI     | Lawful Interception (or Licensee, depending on context) |
| LOS    | Line of Sight                                           |
| LTE    | Long-Term Evolution                                     |
| MCC    | Mobile Country Code                                     |
| MOCN   | Multiple Operator Core Network                          |
| MS     | Mobile Service                                          |
| MSS    | Mobile-Satellite Service                                |
| NB-NTN | Narrowband Non-Terrestrial Network                      |
| NGSO   | Non-Geostationary Orbit (satellite)                     |
| NR     | New Radio (the radio interface for 5G)                  |
| NTN    | Non-Terrestrial Network                                 |
| OEM    | Original Equipment Manufacturer                         |
| PFD    | Power Flux Density                                      |
| PLMN   | Public Land Mobile Network                              |
| PNT    | Positioning, Navigation, and Timing                     |
| QPSK   | Quadrature Phase-Shift Keying                           |
| R&D    | Research and Development                                |
| RACH   | Random Access CHannel                                   |
| RAN    | Radio Access Network                                    |
| RAT    | Radio Access Technology                                 |
| RoI    | Return on Investment                                    |
| TRxP   | Transmission and Reception point                        |

|           |                                                                                               |
|-----------|-----------------------------------------------------------------------------------------------|
| SA1/2/3/4 | Technical Specification Group Service and System Aspects Working Groups 1/2/3/4 (within 3GPP) |
| SCADA     | Supervisory Control And Data Acquisition                                                      |
| SCS       | Subcarrier Spacing (in 5G NR)                                                                 |
| SE        | Spectral Efficiency                                                                           |
| SIB       | System Information Block                                                                      |
| SINR      | Signal-to-Interference-plus-Noise Ratio                                                       |
| SMF       | Session Management Function (in 5G core network)                                              |
| SNO       | Satellite Network Operator                                                                    |
| SNS       | Satellite Navigation System                                                                   |
| SoC       | System on a Chip                                                                              |
| SOS       | Save Our Souls (distress signal)                                                              |
| TDD       | Time Division Duplex                                                                          |
| TN        | Terrestrial Network                                                                           |
| TRxP      | Transceiver Point (or Transmit/Receive Point)                                                 |
| UAS       | Unmanned Aircraft System                                                                      |
| UE        | User Equipment (the device a user holds, e.g., a phone)                                       |
| UL        | Uplink                                                                                        |
| UPF       | User Plane Function (in 5G core network)                                                      |
| V-CHF     | Visited Charging Function (in 5G core network)                                                |
| VPLMN     | Visited Public Land Mobile Network                                                            |
| VSAT      | Very Small Aperture Terminal                                                                  |
| WP        | Working Party (often used in ITU)                                                             |
| WRC-23    | World Radiocommunication Conference 2023 (an ITU conference)                                  |
| WW        | Worldwide                                                                                     |

## References

- 1 Tech space 2.0, key revenue trends in Satellite Communications <https://ts2.tech/en/global-satellite-and-space-industry-report-2025-market-overview-and-outlook-to-2030/> <https://sia.org/news-resources/state-of-the-satellite-industry-report/>
- 2 <https://sia.org/news-resources/state-of-the-satellite-industry-report/>
- 3 ITU Working Party 4C Chair's Report, 21 October 2024, WORKING DOCUMENT ON SHARING AND COMPATIBILITY STUDIES IN RELATION TO WRC-27 AGENDA ITEM 1.13 (WP4C\_AI1.13\_MSS\_Oct24\_R23-WP4C-C-0204!N04!MSW-E)
- 4 Connected Nations update: Spring 2025. <https://www.ofcom.org.uk/phones-and-broadband/coverage-and-speeds/connected-nations-update-spring-2025>
- 5 <https://www.nao.org.uk/wp-content/uploads/2016/09/Upgrading-emergency-service-communications-the-Emergency-services-Network.pdf>
- 6 <https://www.csl-group.com/case-studies/thames-water-vodafone-business-iot/>
- 7 <https://ukpowernetworks.opendatasoft.com/pages/gridandprimarydashboard/>
- 8 <https://digital-strategy.ec.europa.eu/en/news>
- 9 <https://5gaa.org/driving-the-future-5gaa-brings-first-ever-satellite-and-5g-v2x-direct-vehicle-connectivity-to-life-in-paris/>
- 10 <https://the-mobile-network.com/2025/05/5gaa-pushes-ahead-with-first-ntn-and-5g-v2x-direct-demos/>
- 11 ITU-R Document IMT-2020-SAT/4, Evaluation Report on the proposed candidate IMT-2020 satellite radio interface Technology in document IMT-2020-SAT/4, 3 October 2024
- 12 Ofcom Statement and further consultation on Enabling satellite direct to device services in mobile spectrum bands, Published 09 September 2025, <https://www.ofcom.org.uk/siteassets/resources/documents/consultations/category-1-10-weeks/consultation-enabling-satellite-direct-to-device-services-in-mobile-spectrum-bands/main-documents/statement-and-further-consultation-enabling-satellite-direct-to-device-services-in-mobile-spectrum-bands.pdf?v=402573>
- 13 Regulatory guide: Operation of an IMT satellite direct-to-mobile service, <https://www.acma.gov.au/publications/2024-09/guide/regulatory-guide-operation-imt-satellite-direct-mobile-service>
- 14 Direct to Device licensing in New Zealand, Radio Spectrum Management (RSM), <https://www.rsm.govt.nz/licensing/direct-to-device-licensing>
- 15 Framework for D2D satellite services by TCRA, Tanzania, <https://www.tcra.go.tz/uploads/documents/sw-1752839222-GUIDELINES%20FOR%20PROVISION%20OF%20DIRECT%20TO%20MOBILE%20PHONE%20SATELLITE%20COMMUNICATION.pdf>
- 16 Draft CEPT Brief on WRC-27 agenda item 1.13, CPG27-3 Doc. CPG(25)016 ANNEX IV-13, <https://www.cept.org/ecc/groups/ecc/cpg/page/cept-briefs-and-ecps-for-wrc-27>
- 17 <https://www.satellitetoday.com/connectivity/2024/01/16/john-deere-selects-starlink-for-agriculture-connectivity-solution/>
- 18 <https://www.rfwireless-world.com/terminology/iridium-satellite-frequency>
- 19 <https://www.cnn.com/2023/11/09/iridium-announces-end-of-qualcomm-satellite-to-phone-partnership.html>

- 20 <https://investor.iridium.com/2024-09-25-Iridium-Accelerates-Direct-to-Device-Service-with-Acceptance-into-3GPP-Standards-Announces-Iridium-NTN-Direct>
- 21 <https://starlink.com/gb/business/direct-to-cell>
- 22 <https://www.youtube.com/watch?v=0GNdI6OVI3g>
- 23 [https://starlink.com/gb/business/direct-to-cell?srsId=AfmBOorDqpWCytrrhb\\_5SIFWg5zPNFjf2zhJleq9tKiE-RJwbVSFD9I](https://starlink.com/gb/business/direct-to-cell?srsId=AfmBOorDqpWCytrrhb_5SIFWg5zPNFjf2zhJleq9tKiE-RJwbVSFD9I)
- 24 <https://uk.pcmag.com/wireless-carriers/159687/t-mobile-cellular-starlinks-satellite-data-wont-work-on-every-phone#:~:text=Several%20phone%20models%20from%20Samsung%20and%20Motorola%2C,to%20receive%20satellite%20data%20for%20third%2Dparty%20apps.>
- 25 3GPP TSG RAN, "Introduction of NR-NTN in terrestrial bands," New WID on Introduction of NR-NTN in terrestrial bands, RP-252531, Source: Telstra; T-Mobile USA; KDDI; SpaceX; Apple; Mediatek; Qualcomm, Document for Approval, Agenda Item 9.13, 3GPP TSG RAN Meeting #109, Beijing, China, 15–18 Sept. 2025.
- 26 <https://www.spacex.com/updates>
- 27 <https://support.google.com/pixelphone/answer/7158570?sjid=16794206866297369111-EU#zippy=%2Cpixel>
- 28 <https://www.verizon.com/about/news/samsung-galaxy-s25-ultra-verizon-offers>
- 29 <https://uk.pcmag.com/mobile-phones/156417/why-isnt-samsung-talking-about-the-galaxy-s25s-satellite-connectivity>
- 30 <https://uk.pcmag.com/mobile-phones/159713/google-pixel-10-phones-support-satellite-calling-through-whatsapp>
- 31 <https://www.youtube.com/watch?v=0GNdI6OVI3g>
- 32 Economics of D2D satellite lifecycles and replacement strategies, <https://www.telecomtv.com/content/access-evolution/economics-of-d2d-satellite-lifecycles-and-replacement-strategies-53833/>
- 33 Eutelsat, MediaTek and Airbus announce world's first 5G non-terrestrial network connection, leveraging OneWeb LEO satellites, <https://www.mediatek.com/press-room/eutelsat-mediatek-and-airbus-announce-worlds-first-5g-non-terrestrial-network-connection-leveraging-oneweb-leo-satellites>
- 34 Technology overview on Non-Terrestrial Networks (NTN) <https://www.3gpp.org/technologies/ntn-overview>
- 35 IEEE ComSoc publication on Non-Terrestrial Networks, Energy Efficiency and 6G, <https://www.comsoc.org/publications/ctn/non-terrestrial-networks-energy-efficiency-and-6g>
- 36 5G Non-Terrestrial Networks: Technologies, Standards, and System Design by Alessandro Vanelli-Coralli, Nicolas Chuberre, Gino Masini, Alessandro Guidotti, Mohamed El Jaafari, ISBN: 978-1-119-89117-8, January 2024, Wiley-IEEE Press, Link <https://www.wiley.com/en-us/5G+Non-Terrestrial+Networks%3A+Technologies%2C+Standards%2C+and+System+Design-p-9781119891178>
- 37 3GPP, Technical Specification Group Radio Access Network; NR; Radio Resource Control (RRC); Protocol Specification, 3GPP TS 38.331 V18.6.0, Release 18, July 2025. Available: [https://www.etsi.org/deliver/etsi\\_ts/138300\\_138399/138331/18.06.00\\_60/ts\\_138331v180600p.pdf](https://www.etsi.org/deliver/etsi_ts/138300_138399/138331/18.06.00_60/ts_138331v180600p.pdf)
- 38 3GPP, Study on architecture aspects for using satellite access in 5G, 3GPP TR 23.737 V17.2.0, Release 17, July 2021. <https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3485>

- 39** Position paper: Home routing and risks to lawful interception, <https://www.europol.europa.eu/publications-events/publications/position-paper-home-routing-and-risks-to-lawful-interception>
- 40** Roaming in the 5G System: the 5GS roaming architecture, <https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/roaming-in-the-5g-system#:~:text=This%20Ericsson%20Technology%20Review%20article,services%20and%20in%20backe&nd%20systems.>
- 41** 3GPP, Study on charging aspects of satellite in the 5G System (5GS), 3GPP TR 28.844 V18.0.0, Release 18, December 2023. [https://www.3gpp.org/ftp/Specs/archive/28\\_series/28.844/](https://www.3gpp.org/ftp/Specs/archive/28_series/28.844/)
- 42** 3GPP, System architecture for the 5G System (5GS); Stage 2, 3GPP TS 23.501 V19.5.0 (2025-09), [https://www.etsi.org/deliver/etsi\\_ts/123500\\_123599/123501/18.10.00\\_60/ts\\_123501v181000p.pdf](https://www.etsi.org/deliver/etsi_ts/123500_123599/123501/18.10.00_60/ts_123501v181000p.pdf)
- 43** Study on GNSS Resilient NR-NTN Operation, Revised SID, RP-251933 (rev. RP-251863), 3GPP TSG RAN Meeting #109, Beijing, China, Sept. 15–18, 2025
- 44** Introduction of IoT-NTN TDD mode, RP-252872 3GPP TSG RAN meeting document. #109, Beijing, China, Sept. 15–18, 2025.
- 45** 3GPP TS 36.102 V19.1.0 (2025-09), Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception for satellite access, [https://www.3gpp.org/ftp/Specs/archive/36\\_series/36.102](https://www.3gpp.org/ftp/Specs/archive/36_series/36.102)
- 46** 3GPP TSG RAN, "Revised WID: Non-Terrestrial Networks (NTN) for Internet of Things (IoT) Phase 4," RP-252473, Source: vivo (moderator), Document for Approval, Agenda Item 15.2.2, 3GPP TSG RAN Meeting #109, Beijing, China, Sept. 15–18, 2025.
- 47** 3GPP TSG SA, "Stage 1 for Lower Selection-priority for PLMN Selection," New WID on Lower Selection-priority for PLMN Selection, SP-251194 (rev. SP-250978), Source: SA1 (from S1-253628), Document for Approval, Agenda Item 6.1.1, 3GPP TSG SA Meeting #109, Beijing, China, 16–19 Sept. 2025.
- 48** Stage 1 for Lower Selection-priority for PLMN Selection," New WID on Lower Selection-priority for PLMN Selection, SP-251194 (rev. SP-250978), Source: SA1 (from S1-253628), Document for Approval, Agenda Item 6.1.1, 3GPP TSG SA Meeting #109, Beijing, China, 16–19 Sept. 2025.
- 49** 3GPP, "Chair's summary of the 3GPP workshop on 6G", 6GWS-250238, 3GPP workshop on 6G, Incheon, Korea, 10–11 Mar. 2025.
- 50** 3GPP TSG RAN, "NTN related views on 6G RAN WG SI," RP-251001, Source: Thales; TNO; Novamint; Airbus; ESA; Sateliot; SES; Gatehouse Satcom; Eutelsat Group; Iridium, Discussion document for discussion, Agenda Item 16.2 (New RAN WG SI on 6G), 3GPP TSG RAN Meeting #108, Prague, Czech Republic, 9–13 June 2025.
- 51** Vision, requirements and evaluation guidelines for satellite radio interface(s) of IMT-2020, <https://www.itu.int/pub/R-REP-M.2514-2022>
- 52** 3GPP TR 37.911 V19.0.0 (2025-09), Technical Specification Group Radio Access Network; Study on self-evaluation towards the IMT-2020 submission of the 3GPP Satellite Radio Interface Technology (Release 19), [https://www.3gpp.org/ftp/Specs/archive/37\\_series/37.911/](https://www.3gpp.org/ftp/Specs/archive/37_series/37.911/)
- 53** M.1182 : Integration of terrestrial and satellite mobile communication systems <https://www.itu.int/rec/R-REC-M.1182>

- 54** New iPhones have Qualcomm satellite modem, new Apple radio chips, <https://www.reuters.com/technology/new-iphones-have-qualcomm-satellite-modem-new-apple-radio-chips-2022-09-17/>
- 55** <https://www.skylo.tech/certified-devices>
- 56** World's First 5G-A NR-NTN connection over LEO satellites, <https://www.mediatek.com/tek-talk-blogs/worlds-first-5g-nr-ntn-connection-over-leo-satellites>
- 57** Sateliot hails standards-based IoT connection from LEO to a commercial device, <https://spacenews.com/sateliot-hails-first-standards-based-iot-connection-from-leo-to-a-commercial-device/>
- 58** 3GPP TR 37.911 V19.0.0 (2025-09) Technical Specification Group Radio Access Network; Study on self-evaluation towards the IMT-2020 submission of the 3GPP Satellite Radio Interface Technology (Release 19), [https://www.3gpp.org/ftp/Specs/archive/37\\_series/37.911](https://www.3gpp.org/ftp/Specs/archive/37_series/37.911)
- 59** 3GPP TR 38.821 V16.2.0 (2023-03), Technical Specification Group Radio Access Network; Solutions for NR to support non-terrestrial networks (NTN) (Release 16) [https://www.3gpp.org/ftp/Specs/archive/38\\_series/38.821/](https://www.3gpp.org/ftp/Specs/archive/38_series/38.821/)
- 60** 3GPP TS 38.214 V19.1.0 (2025-09), Physical layer procedures for data (Release 19)
- 61** RP-232647 (revision of RP-231499), 30 MHz Channel Bandwidth for NR NTN in FR1, THALES, 3GPP TSG-RAN Meeting #101, Bengaluru, India, 11–14 Sep 2023, for Approval, Agenda Item 9.4.5.4.
- 62** 3GPP TR 37.911 V18.1.0, "Study on self-evaluation towards the IMT-2020 submission of the 3GPP Satellite Radio Interface Technology," May 2024.
- 63** Office for National Statistics, <https://www.ons.gov.uk/>
- 64** Using 3GPP technology for satellite communication, <https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/3gpp-satellite-communication>

Real Wireless Ltd  
PO Box 2218  
Pulborough  
West Sussex  
RH20 4XB  
United Kingdom

**t** +44 207 117 8514  
**f** +44 808 280 0142  
**e** [info@real-wireless.com](mailto:info@real-wireless.com)  
**w** [real-wireless.com](http://real-wireless.com)  
**in** [real-wireless](https://www.linkedin.com/company/real-wireless)