DIRECT-TO-CELL TECHNOLOGY: ENABLING SATELLITE CONNECTIVITY FOR LEGACY DEVICES

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CONTENTS

1 INTRODUCTION TO NON-TERRESTRIAL SERVICES

The complement of terrestrial wireless networks by non-terrestrial services has achieved the status of reality. Initial services like emergency messages sent over satellites have been deployed and commercialized. New services and enhancements of the existing technology of non-terrestrial networks (NTN) are being discussed in standard development organizations like 3GPP and implemented in the initial products. In recent years, low earth orbit (LEO) mega-constellations have become viable and increasingly widespread. A non-terrestrial network (NTN) offers connectivity services for mobile satellite services (MSS) and fixed satellite services (FSS). Satellite networks like SpaceX's Starlink, Eutelsat's OneWeb or Amazon's Kuiper are in operation and provide internet connectivity to the end user.

The technology evolution that is occurring in the areas of satellite launching systems, digital signal processing and embedded computing stages as well as sophisticated antenna systems supporting beamforming is trailblazing the system deployment. 3GPP specifications began with Release 17 to enable NTN and incorporate several technological aspects into the series of specifications. To offer services with a fast time-to-market approach, the idea in the background of direct-to-cell (DTC) is to offer satellite connectivity to end user devices without the need for an updated device. In other words, DTC brings wireless communications services based on 4G, LTE technology to unmodified and commercially available devices.

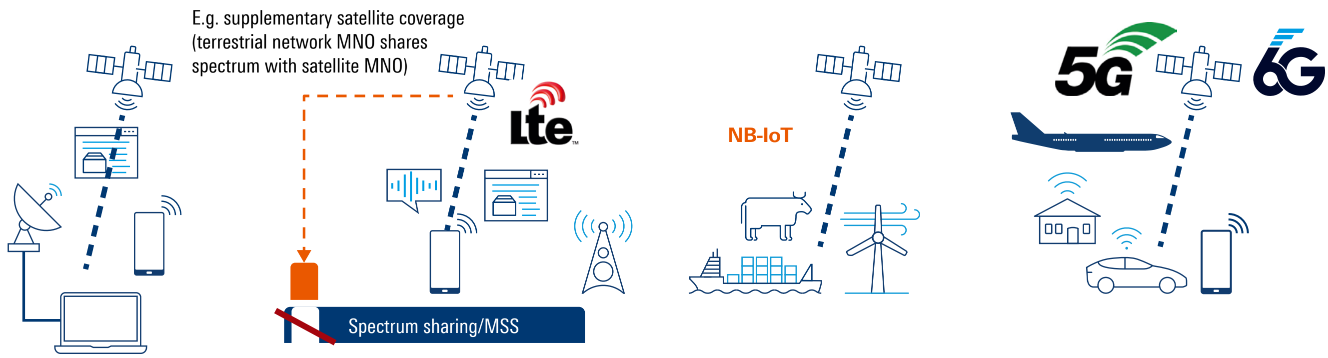
Decisions by spectrum regulatory bodies like the USA FCC SCS document [Ref. 4] or the SpaceX Starlink – Echostar spectrum acquisition deal are paving the spectral foundation of frequencies that can be used to offer satellite-based connectivity services. This is handled currently through national regulation, while policies are being implemented to ensure a fair spectral neighborhood with incumbent communications services. On this basis, real service offerings have been announced for subscribers in the USA, Europe or Australia, to name only a few examples. For details, see [Ref. 12], [Ref. 13] and [Ref. 18].

In this document, we will look at a few of the technological details of how DTC brings internet connectivity via satellite communications to the end user. This document should be used alongside a series of other documents provided by Rohde & Schwarz. First, there is the existing white paper on NTN technology in [Ref. 2] and second, there is a new technical document describing the details of NTN technologies like architectures, mobility, protocol procedures and testing in [Ref. 3]. A general overview of satellite communications and other satellite-related topics like orbit information, constellations or flight coordination is provided in the pocket guide [Ref. 5].

1.1 Market and standardization situation of NTN

Although satellite communications has been available for decades, we consider 5G as the first wireless technology that seriously considers how to enable non-terrestrial networks and offer satellite connectivity services in a holistic approach, interworking with terrestrial and non-terrestrial networks with the long-term objective of seamless connectivity. As described in [Ref. 2], the standardization organization 3GPP started a study item with Rel. 15 to investigate whether and how 5G can enable non-terrestrial communications. This study item was then continued and enhanced with Rel. 16 and ended up in the specification of several technology updates in Rel. 17. We consider Rel. 17 as the technology baseline for NTN, while Rel. 18 and current Rel. 19 introduce new technology enhancements. Initial workshops and meetings have happened with the aim of agreeing on initial 6G technology components. At least one consensus is obvious: Non-terrestrial networks will play a pivotal role in future architecture designs of 6G as the objective for 6G will be the design of a 3D unified network. As the current market situation reveals an urgent need to provide ubiquitous communications, even in remote or maritime areas, or support public protection disaster relief (PPDR) services, there is strong demand for satellite-based communications among subscribers and industry. As a complement to the standardization work in 3GPP, some proprietary solutions are also appearing on the industrial horizon and a technology workaround based on existing communications will be deployed, offering NTN use cases in an early time-to-market approach. Therefore, we currently distinguish between four different paradigms of NTN as shown in Figure 1.

Figure 1: Non-terrestrial networks and current market situation with four paradigms



Non-3GPP satellite communications

- Smartphone with additional RF frontend and modem
- Dedicated spectrum
- Satellite constellation available
- Dedicated use cases: e.g. messaging
- Dedicated ecosystem

Direct-to-cell (DTC) communications

- Legacy smartphone
- Spectrum sharing or MSS spectrum
- Doppler compensation at satellite → efficiency!
- Early service offering (time to market)
- Limited efficiency and capacity

4G/5G IoT-NTN (satellite NB-IoT)

- Rel. 17+ IoT devices
- Dedicated satellite spectrum (S-band and L-band); < 6 GHz
- Limited capacity, low data rate
- Best effort QoS, delay tolerant
- 4G NB-IoT based, future 5G (e)RedCap

NR-NTN/5G NTN (satellite to everything)

- New silicon UE with Rel. 17+ capabilities, various categories, from smartphone to VSAT
- Dedicated spectrum, first < 6 GHz, second Ku-band and Ka-band and others
- Higher capacity, multiple use cases

In this figure we depict the four current paradigms of NTN. In the remainder of this document, we will delve further into DTC-related topics.

Non-3GPP satellite communications

As satellite communications is not an invention of 3GPP standardization, we should recall the existing satellite communications network landscape. Most parts apply proprietary or non-3GPP waveforms, use a dedicated system architecture, and are based on an ecosystem of suppliers, operators and users. To offer communications services and connectivity as a complement to 5G, there have been some bilateral negotiations and cooperations agreed between satellite network operators (SNO), user equipment (UE) vendors and infrastructure suppliers that target the provision of NTN services in an early phase. These negotiations ended with an agreement where UE vendors have upgraded or extended their hardware and software capabilities in a way that allows the devices to support such proprietary satellite communications at least in a basic manner. A well-known user application involves the possibility to send an emergency message via satellite in remote areas with a smartphone, updated with non-3GPP methods. These technologies and services are entirely based on such joint agreements between different vendors and are not standardized. For further enhancement taking advantage of the fact that 3GPP introduced a very flexible system with 5G that also enables interworking with non-3GPP access technologies, there are several interworking scenarios feasible within the ecosystem.

Direct-to-cell (DTC) communications

Like the non-3GPP access technologies supporting satellite communications, DTC aims at an early time-to-market approach. The difference here is that the network, in our case the satellites and terrestrial architecture, are incorporating and offering legacy wireless communications technologies like EUTRAN (4G or LTE) or 5G New Radio (5G NR) in a later phase. The objective is to achieve a spaceborne cell tower approach that offers connectivity to the UE that is agnostic of the terrestrial or satellite nature of the radio interface. The ensuing requirement in order to counter the difficulties that arise is that the network must implement tweaks to compensate and eliminate physical layer challenges like time delay, Doppler frequency shift or signaling procedure handling. This requires some changes based on EUTRAN or 5G technology, but recall that since EUTRAN or 5G offer some flexibility, such network-based adaptations do not conflict with existing specifications, but are still fully compliant with the standards. The drawback in compensating for such network physical-layer issues is the impact of physics that render countermeasure implementation inefficient and leave certain challenges unhandled.

5G internet of things NTN (IoT-NTN)

This paradigm represents the possibility to enhance legacy IoT technology like the 4G-based NB-IoT to enable NTN services as described in Rel. 17 and later releases. IoT-NTN introduces a couple of technology enhancements like mandated support of GNSS navigation in the UE, new system information blocks informing about satellite ephemeris, and a couple of timer offsets to tackle the latency aspects. In addition, like NR-NTN, the UE must pre-compensate for the Doppler shift in the downlink and uplink directions. More details can be found in [Ref. 2] and in a future white paper that will be published soon [Ref. 3]. Check the Rohde & Schwarz website for updates.

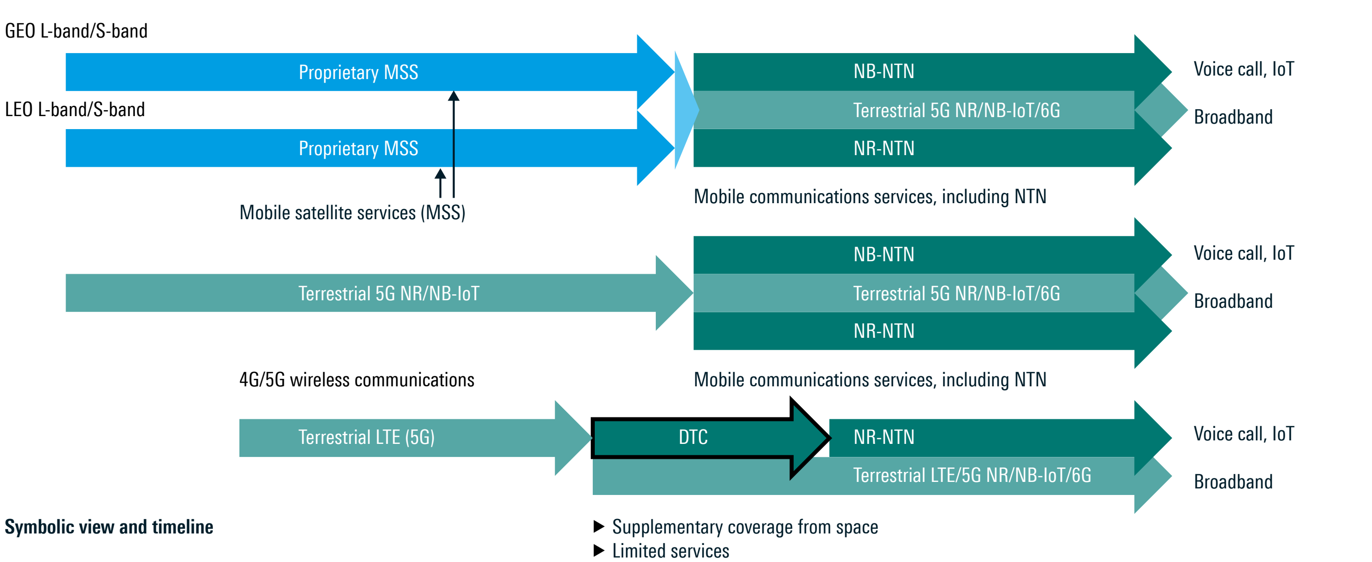
5G NR-NTN

With Rel. 17, 3GPP introduced NTN into its specifications for the 5G system with the objective being for 5G to enable non-terrestrial communications. Enhancements are specified in Rel. 18, current Rel. 19 and future Rel. 20. 5G NTN (NR-NTN) introduces introduces many technical details into the series of specifications (see [Ref. 2] and [Ref. 3]). The drawback is that NR-NTN needs updates on both the network and UE side and is seen as a waypoint for long-term evolution. The advantages include the flexibility and efficiency of NR-NTN with its technology maturity. Future NTN networks will use additional frequency bands, wider bandwidth but also introduce new UE form factors like the VSAT type of UE for vehicle, stationary, maritime or avionic deployments. In the long term, NR-NTN is a trailblazer in the 6G evolution, which is expected to specify a 3D unified network architecture with multi-orbit satellite constellations and added airborne-based network nodes.

1.2 Timeline estimate for the NTN and DTC evolution

Another perspective takes account of the evolutionary path towards the introduction of NTN services. As already mentioned in [Ref. 2], we consider NTN as a convergence between two ecosystems, i.e. aerospace and wireless communications. This concludes in different evolutionary paths. A legacy satellite operator providing MSS (and/or FSS) use cases either via LEO or GEO satellites can re-farm spectrum or complement its spectrum and use cases by introducing 5G NTN services, either IoT-NTN or NR-NTN or both. This also includes roaming or cooperation agreements with incumbent mobile network operators (MNO). As a simplification, we denote this evolutionary path as "aerospace offering wireless". The opposite evolution is then "wireless offering aerospace", or better, "NTN". The most prominent path involves the introduction of NR-NTN into 5G NR networks as described by Rel. 17. With a faster time-to-market approach, DTC would then offer a third path, heading from a legacy 4G network like LTE directly into NTN services. As there might be some efficiency issues, we consider DTC as an interim stage before NR-NTN is fully deployed.

Figure 2: Evolutionary path to NTN services



2 DIRECT-TO-CELL (DTC) TECHNOLOGY OVERVIEW AND CHALLENGES

The term direct-to-cell (DTC/D2C) does not represent a specified technical term, nor does it correspond to a single specific technology that is introduced in 3GPP releases. The aim is to work with existing commercially available LTE devices without requiring special hardware or software enhancements to enable services like texting, calling and basic data even where no cell towers exist. Some examples are provided in [Ref. 18]. DTC relies on advanced satellite modems that act like cell towers in orbit. As mentioned in the introduction, DTC can be described as a kind of workaround to introduce some tricks and tweaks, especially on the network side, to enable satellite communications in a very early time-to-market approach. The objective is to deliver satellite communications to state-of-the-art commercial mobile devices or those that require only minor software updates. But since the market relevance is growing and this idea is gaining momentum, we would like to introduce some technical aspects of DTC. Besides the term direct-to-cell (DTC/D2C), several other names coexist, like direct-to-handheld (D2H/DTH), direct-to-device (D2D) or direct satellite-to-device (DS2D). For consistency, we will stick with the abbreviation DTC across this document. Our understanding of DTC corresponds to a 4G (LTE) satellite-based network offering communications services to 4G devices (unmodified). Future updates may also include 5G standalone networks, but without the technical features introduced in Rel. 17. In a mid-term to long-term view, we expect that NR-NTN will supersede DTC connectivity. The network will implement some “tweaks” to enable those services. The advantage lies in an early time-to-market approach, with the drawback being certain technical issues that affect the overall system efficiency. There is no consensus on spectrum, i.e. spectrum sharing might be an option, or a re-farming of existing spectrum for legacy MSS applications now for DTC. In some discussions, we have observed that the term DTC is also used as a very generic and general term for the provision of satellite communications services to handheld form factor devices without any connection to a specific radio technology.

2.1 Concise technology overview

There is no dedicated technical specification for DTC; it is based on the 3GPP EUTRAN series. However, some technical methods are applied in a proprietary manner, i.e. defined by the satellite network operator with the objective to provide 4G radio access to end user devices via satellite. Some of these technology changes or methods are obvious or are known to be incorporated into the networks to successfully enable NTN services. The satellite constellation is restricted to LEO only due to the round-trip time aspects. SpaceX Starlink targets the lowest feasible orbital altitudes around 550 km with a very high constellation density. AST SpaceMobile relies on a less dense constellation but at slightly higher altitudes of around 700 km. See [Ref. 19] for information on satellite constellations.

Rather than awaiting the completion of 3GPP standardization of NTN, SpaceX Starlink pursued an early deployment strategy by integrating conventional LTE eNodeB payloads into its satellites, complemented with proprietary adaptations for NTN operation. This allows smartphones to connect natively using terrestrial mobile communications standards, while traffic is handled either through the company’s ground station network or, when necessary, routed across the constellation via inter-satellite links (ISL) [Ref. 10].

Regarding the physical layer challenges like Doppler shift, time delay or polarization rotation, there is a controversial understanding between DTC and NR-NTN. In DTC, the approach is to implement some pre-compensation methods on the network side, while the 3GPP opinion is that the UE needs to perform such pre-compensation while the network side provides support through system information provisioning. In summary, these technical aspects need to be tackled by DTC.

- LTE DTC should work with many devices today, i.e. the objective is to provide a satellite-based cell on the earth that “cannot” be distinguished from a terrestrial cell. This implies quasi-earth fixed multi-beam LEO satellites in a dense constellation.

- LTE evolved NodeB (eNB) performs Doppler compensation at least for an earth reference point and the eNB also performs some time delay compensation as the legacy LTE method of timing advance adaptation is too slow and might only contribute to but not solve the delay problem.

- It is not defined at what level any updates on the UE side are necessary. However, the vendor will probably offer a kind of updated software version that may cope with some issues. The implications in a DTC cell are a higher carrier frequency offset due to Doppler shift, as well as a large frequency change when performing handover because of the change from an "incoming" flight route satellite to an "outgoing" flight route satellite.

- LEO satellites with narrow beam footprint and multi-beam architecture. The long time delay and especially the challenge with random access restricts the DTC architecture to LEO constellations only. As the satellite will compensate for the Doppler effect, the beam footprint has to be narrow, but for better capacity, the satellite will then offer multiple beams in parallel. Another impact is that the satellite needs to operate in regenerative payload due to the long delay and random access channel issues.

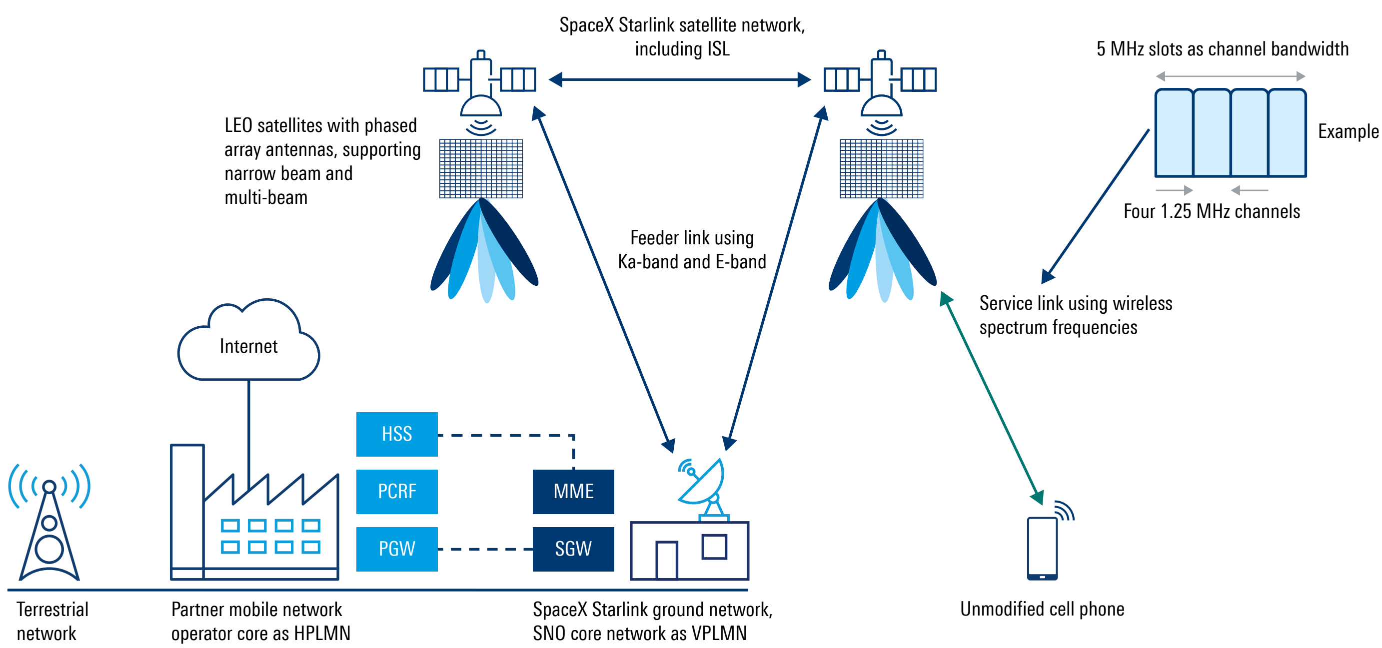
- There is no dedicated spectrum for DTC. The offering can either use spectrum sharing models where terrestrial and satellite operators share their spectrum, or it can be legacy spectrum for MSS use cases that can be used for DTC, depending on the regulatory policies.

- The core network remains on the ground and the architecture model understands the DTC as a satellite network with the SNO as a visited public land mobile network (VPLMN) and the terrestrial MNO as a home public land mobile network (HPLMN).

- HPLMN is responsible for end-to-end (E2E) connectivity, user policy control and authentication and regulatory tasks like lawful interception.

- The satellite will pre-compensate the Doppler in the downlink direction and post-compensate the Doppler in the uplink direction by both carrier and sampling frequency offset compensation.

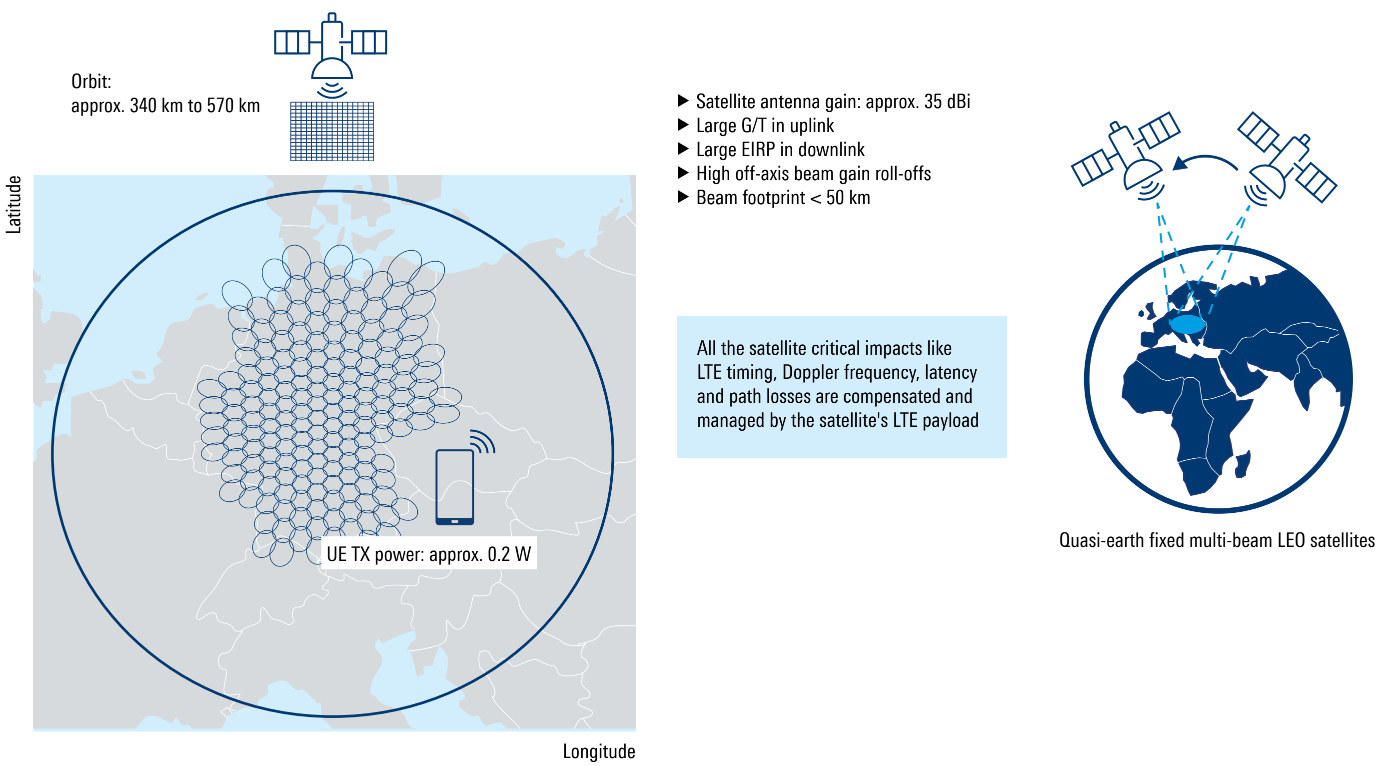
Figure 3: Direct-to-cell, general architecture



2.2 Feature overview

In a European Conference of Postal and Telecommunications Administrations (CEPT) technical report, satellite DTC is described as additional base stations complementing the service area of a terrestrial MNO under its existing authorizations and supervision [Ref. 6]. The core element of the SNO and MNO cooperation is the maintenance of the MNO's end-to-end responsibility for service provisioning and legal aspects like license and regulatory aspects as well as subscribers' policy obeyance. The satellite segment is simplified as a space-based cellular tower. The allocated frequency on the service link is either based on spectrum sharing or MSS allocation and the feeder link uses spectrum in the Ka-band and E-band in current deployments. The main aspects related to the satellites are the operation in LEO orbit with a quasi-earth fixed multi-beam approach. The satellites use phased array antennas with a high gain to compensate for the path loss. The path loss is elevation angle dependent and due to the low orbital altitude, we face a distance change between approx. 1500 km at 30° elevation and approx. 500 km at 90° elevation [Ref. 6]. The satellite beam footprints may vary. Figure 4 shows an example of coverage over Germany.

Figure 4: Direct-to-cell, feature overview



A short comparison between DTC and NR-NTN indicates the characteristics of DTC and NR-NTN given as [Ref. 7].

Table 1: Comparison between DTC and 3GPP NR-NTN and IoT-NTN

Item	Direct-to-cell	NR-NTN/IoT-NTN
Radio access technology	EUTRAN/LTE	5G NR/NB-IoT
Devices	▶ Currently commercially available smartphones ▶ Handheld	▶ Under development ▶ New chipset required ▶ Long-term: VSAT type UEs ▶ First IoT-NTN chipsets available
Network architecture	▶ LEO orbit with regenerative payload eNB ▶ Limited flexibility	▶ High flexibility ▶ Transparent and regenerative payload ▶ Priority: LEO and GEO but other constellations possible ▶ Unified 3D network in 6G
Spectrum	▶ FR1, < 6 GHz ▶ As spectrum sharing or MSS	▶ FR1 for IoT-NTN and NR-NTN phase 1 ▶ NR-NTN phase 2
Spectrum regulation	National regulation, allocation on national area only	▶ 3GPP specified bands ▶ ITU regulation framework
Performance	▶ Limited use cases and services ▶ Priority 1: emergency, short data, basic voice	▶ Robust ▶ Data rates around several Mbps up to dozen Mbps at higher bands
Time and Doppler compensation	Satellite compensates for time and Doppler	▶ Satellite provides assistance information via system information ▶ UE compensates for Doppler and timing advance
Mobility	Based on LTE handover, signaling overhead	Sophisticated mobility procedures like conditional handover, LTM and RACH-less up to multi-connectivity
Business situation	▶ Very optimistic, offers services by today ▶ Long-term: transfer to NR-NTN	▶ NR-NTN not yet commercially ready ▶ IoT-NTN services available
Testing aspects	Based on EUTRAN, operator specific test scenarios	▶ 3GPP specified ▶ GCF and PTCRB conformance testing ▶ Operator specific testing

DTC: Uses terrestrial 4G LTE as the wireless communications technology, is mature and widely available, has limited flexibility and may face limitations, but is available on the short term and offers a pragmatic solution leveraging the ecosystem of legacy devices.

NR-NTN: Is purpose-built for NTN support, still under development and requires new chipset and infrastructure entities, supports flexible and wide range of applications in dedicated spectrum bands based on international regulated framework and offers robust and future-proof concept, but is understood as the mid-term to long-term approach.

2.3 Spectrum aspects

As DTC is not a specified technology update within the 3GPP system, there is no dedicated spectrum allocated to its use cases. By way of overview, two kinds of spectrum access models exist. In a terrestrial mobile spectrum model, the satellite network operator (SNO) obtains authorization to operate within the mobile spectrum (MS) that is currently allocated for terrestrial usage. In contrast, the mobile satellite spectrum (MSS) model uses spectrum allocated to MSS in the ITU radio regulations for DTC, described below as DTC overlay [Ref. 7].

In March 2024, the USA FCC launched a document FCC SCS “FCC Advances Supplemental Coverage from Space Framework” [Ref. 4] that allows operators to share spectrum between terrestrial and non-terrestrial networks. As commercial services, the US operator T-Mobile agreed with the satellite operator SpaceX Starlink to operate on T-Mobile’s 5 MHz of LTE band 25 (1952.5 MHz).

With respect to spectrum usage for DTC, two major deployment concepts may be used: spectrum sharing or DTC overlay. As an example, we present the coverage situation in USA and Germany in the following figure. Both countries have white patches in their terrestrial coverage as most likely every terrestrial network does. The difference is that in geographically large countries, the uncovered areas are relatively large, while densely populated countries exhibit a kind of patchwork coverage situation where the white patches are relatively small but widely distributed across the entire region. A spectrum sharing concept where terrestrial and non-terrestrial operators share spectrum may cause some coexistence issues. In the latter case, the MNO probably would seek an overlay spectrum deployment where band A is used for the TN and band B for the NTN to avoid coexistence issues.

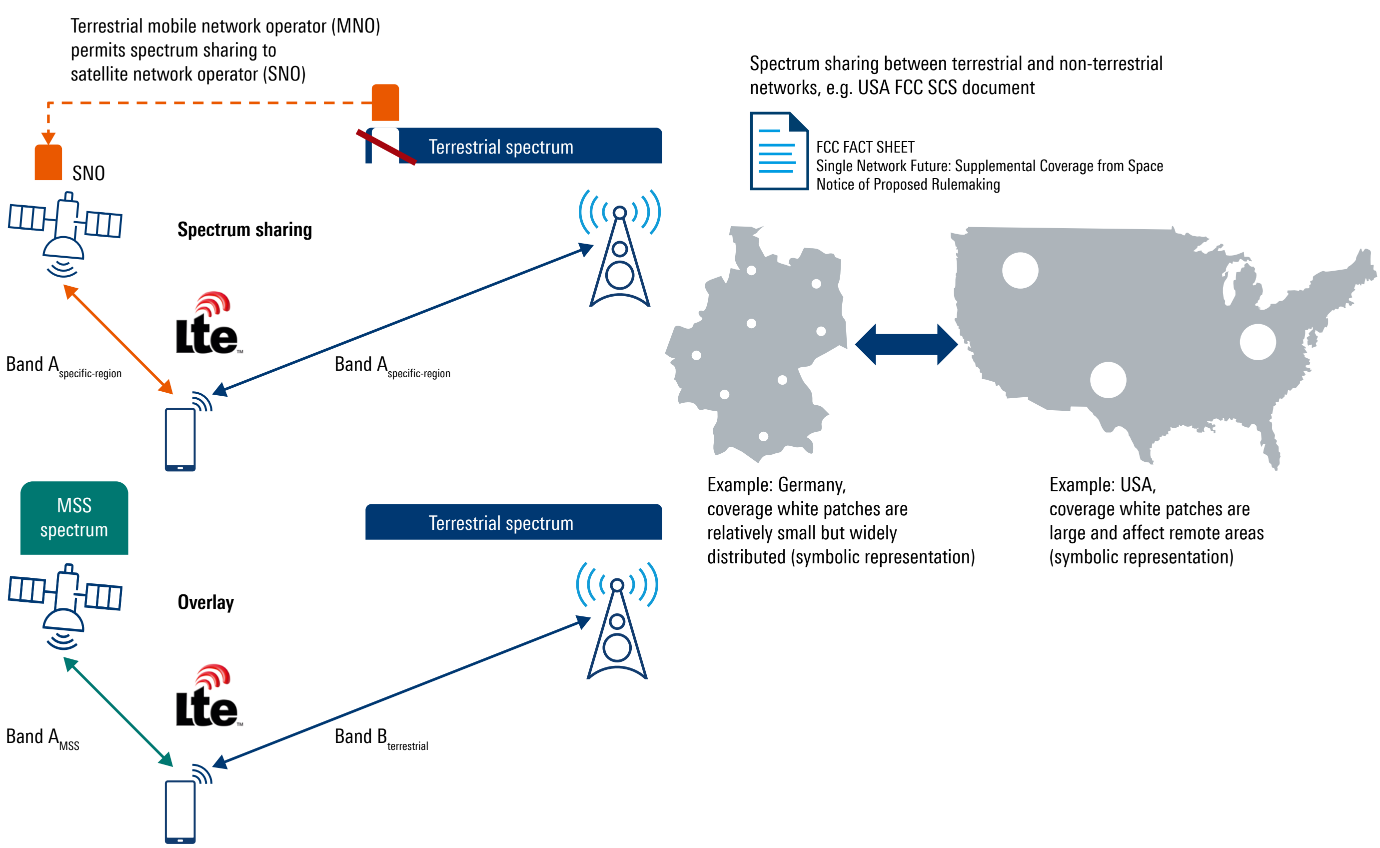
When deploying D2D satellite communications in terrestrial mobile bands, some spectrum coexistence issues may occur. Ensuring the protection of terrestrial networks requires control over satellite transmission parameters. The CEPT requires some measures like out-of-band emission control or transmit power reduction [Ref. 6]. In addition, geographic separation mechanisms must be implemented to prevent co-channel interference with terrestrial systems in adjacent areas. This often requires exclusion zones – areas within a satellite's footprint where transmissions are suppressed to protect terrestrial devices and base stations. The size of these zones is typically equivalent to a satellite spot beam, which can limit the coverage [Ref. 7].

In 2025, a commercial deal between the satellite operators SpaceX Starlink and Echostar included the sale of frequency spectrum in certain regions.

Key spectrum bands acquired by SpaceX:
- AWS-4 (S-band): 2000 MHz to 2020 MHz, 2180 MHz to 2200 MHz
- AWS-3: 1695 MHz to 1710 MHz (uplink), part of 3GPP band 70n
- H-block: part of the S-band

Within 3GPP, the request came up to enable the terrestrial bands n7 (2500 MHz to 2570 MHz in uplink and 2620 MHz to 2690 MHz in downlink) and n25 (1850 MHz to 1915 MHz in uplink and 1930 MHz to 1995 MHz in downlink) for NR-NTN and optionally for DTC [Ref.20].

Figure 5: DTC spectrum aspects, spectrum sharing or overlay deployment



The ITU-R is considering new MSS allocations in the 700 MHz to 2700 MHz range to support direct satellite-to-international mobile telecommunications (satellite-to-IMT) UE connectivity to complement terrestrial network coverage under World Radio Conference 2027 (WRC-27) agenda item 1.13; see [Ref.8].

As examples of potential spectrum candidates that are under discussion for NR-NTN but also DTC, see the following European Common Allocation (ECA) table [Ref. 6].

Table 2: Spectrum allocation table for mobile services and mobile satellite services in Europe

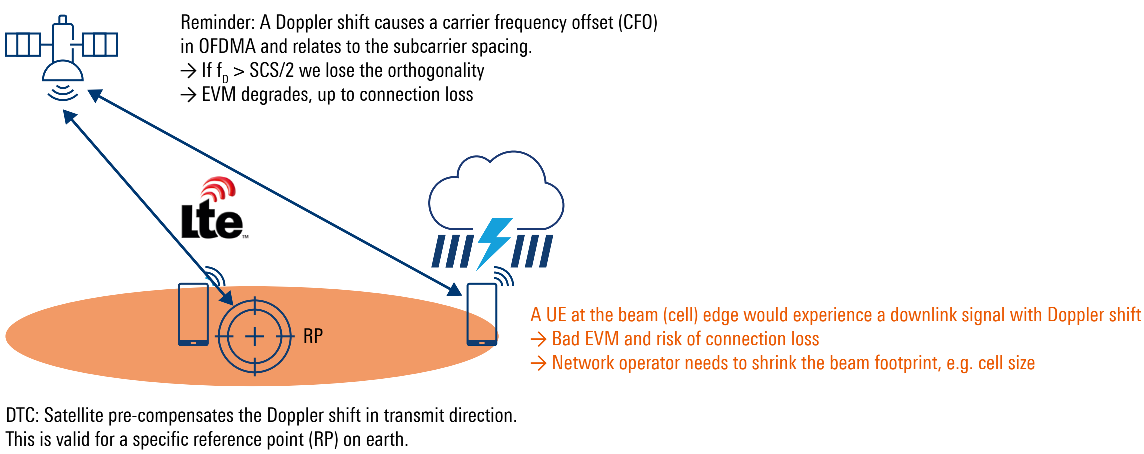
Frequency allocations: European Common Allocation (ECA)

Frequency band	Mobile service (MS)	Mobile satellite services (MSS)
694 MHz to 862 MHz	Mobile except aeronautical mobile	
862 MHz to 960 MHz	Mobile	
1350 MHz to 1400 MHz	Mobile	
1427 MHz to 1518 MHz	Mobile except aeronautical mobile	
1518 MHz to 1525 MHz	Mobile except aeronautical mobile	Mobile satellite (space-to-earth)
1525 MHz to 1530 MHz		Mobile satellite (space-to-earth)
1530 MHz to 1535 MHz	Mobile except aeronautical mobile	Mobile satellite (space-to-earth)
1535 MHz to 1559 MHz		Mobile satellite (space-to-earth)
1610 MHz to 1610.6 MHz		Mobile satellite (earth-to-space)
1610.6 MHz to 1613.8 MHz		Mobile satellite (earth-to-space)
1613.8 MHz to 1621.35 MHz		▶ Mobile satellite (earth-to-space) ▶ Mobile satellite (space-to-earth)
1621.35 MHz to 1626.5 MHz		▶ Maritime mobile-satellite (space-to-earth) ▶ Mobile satellite (earth-to-space) ▶ Mobile satellite (space-to-earth)
1626.5 MHz to 1660 MHz		Mobile satellite (earth-to-space)
1660 MHz to 1660.5 MHz		Mobile satellite (earth-to-space)
1660.5 MHz to 1668 MHz	Mobile except aeronautical mobile	
1668 MHz to 1668.4 MHz	Mobile except aeronautical mobile	Mobile satellite (earth-to-space)
1668.4 MHz to 1670 MHz	Mobile except aeronautical mobile	Mobile satellite (earth-to-space)
1670 MHz to 1675 MHz	Mobile	Mobile satellite (earth-to-space)
1675 MHz to 1690 MHz	Mobile except aeronautical mobile	
1690 MHz to 1700 MHz	Mobile except aeronautical mobile	
1700 MHz to 1710 MHz	Mobile except aeronautical mobile	
1710 MHz to 1980 MHz	Mobile	
1980 MHz to 2010 MHz	Mobile	Mobile satellite (earth-to-space)
2010 MHz to 2170 MHz	Mobile	
2170 MHz to 2200 MHz	Mobile	Mobile satellite (space-to-earth)
2200 MHz to 2290 MHz	Mobile	
2290 MHz to 2300 MHz	Mobile except aeronautical mobile	
2300 MHz to 2483.5 MHz	Mobile	
2483.5 MHz to 2500 MHz	Mobile	Mobile satellite (space-to-earth)
2500 MHz to 2690 MHz	Mobile except aeronautical mobile	
2520 MHz to 2655 MHz	Mobile except aeronautical mobile	
2655 MHz to 2670 MHz	Mobile except aeronautical mobile	
2670 MHz to 2690 MHz	Mobile except aeronautical mobile	

2.4 Doppler shift causing carrier frequency offset (CFO)

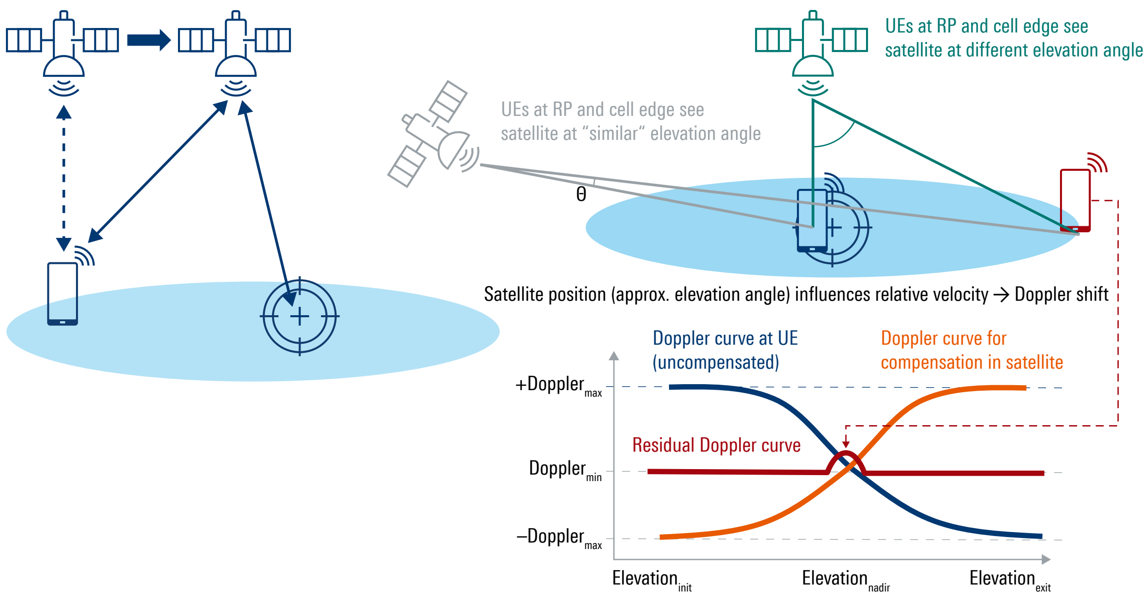
A LEO satellite travels at a high velocity that causes a Doppler shift, as explained in [Ref. 2]. The challenge is that a Doppler shift causes a carrier frequency offset (CFO) and OFDMA systems are very sensitive to such a CFO. If the frequency offset exceeds the half of the subcarrier spacing (SCS), OFDMA loses the orthogonality, and the call may even drop. There is now a fundamental difference between 3GPP NTN and DTC. In 3GPP NTN, it is the task of the UE to compensate for such an impact due to Doppler shift. The network supports this by broadcasting ephemeris information via system information [Ref. 3]. In DTC, the assumption is that the network will compensate for such Doppler, and ideally the UE should not see any difference between TN and NTN cells. But such Doppler shift compensation is only valid for a specific location within the beam footprint, i.e. at a reference point (RP). A UE located at the cell edge would then experience a residual Doppler shift, meaning that the network operator needs to shrink the beam footprint or cell size. Typical values are 30 km to 50 km maximum. The ITU-R requirements in M.2514 describe a satellite with a 1.76° beamwidth. Thus, in a LEO orbit at 600 km, the nadir cell diameter would be 18.5 km [Ref. 9]. To leverage such strategies, one assumption is that the satellite operates based on a quasi-earth-fixed beam concept and supports multiple beams in parallel. In addition, a satellite operating in regenerative payload might have more processing capabilities to handle such compensation methods.

Figure 6: Doppler shift causing carrier frequency offset



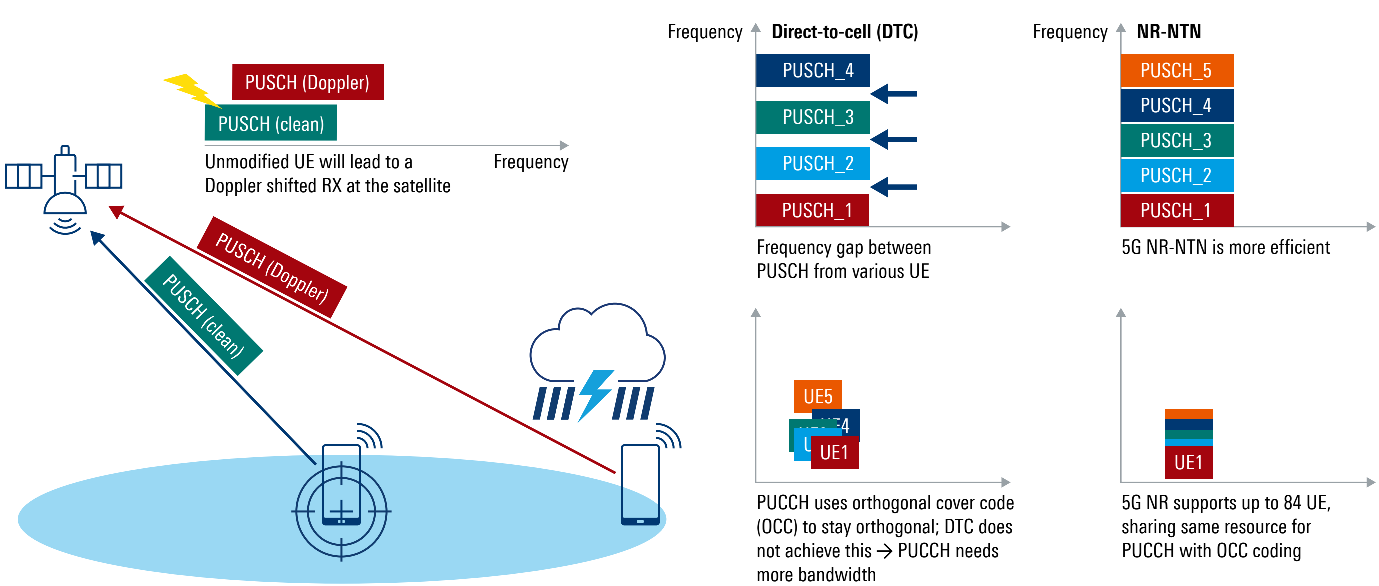
In practice, assuming no pre-compensation, the UE or any receiver on the ground would see the downlink signal shifted by a Doppler or carrier frequency shift that reveals an S-shape behavior (see also [Ref. 2] and Figure 7). The aim is for the satellite to internally compensate for this Doppler, but only related to a specific destination on earth, marked as the reference point (RP). Note that unlike NR-NTN, this reference point is not revealed to the UE. The satellite would then calculate and apply a compensation frequency to pre-compensate this Doppler, mathematically representing the inverse of the Doppler shifted frequency. As explained, this might only work for a specific reference point within the beam footprint. In our assumption, the UE is located at a residual offset away from the reference point. Consequently, the UE might experience a residual Doppler shift as shown in the figure. The relative velocity of the satellite versus the UE, relevant for the frequency offset, is elevation angle dependent, as shown. For that reason, the symbolic indication of the residual Doppler is higher if the satellite is more in a perpendicular position. The worst-case difference in Doppler shift across the cell is when the satellite is directly above the center of the cell at nadir position. With a 1.76° beamwidth and a satellite speed of 7500 m/s, at the cell edge the speed towards/away from the satellite is 415 km/h [Ref. 9]. Some vendor trials have demonstrated that Doppler effects at this speed can be handled.

Figure 7: Doppler shift pre-compensation strategy



Another challenge related to the carrier frequency offset due to the satellite velocity exists in the uplink direction. Remember that the UE synchronizes to the received frequency in the downlink direction. The synchronization signals help with this task. In the uplink direction, the UE uses the frequency with the standardized uplink-downlink duplex distance (in FDD). The assumption is that any frequency deviation due to UE velocity is small. With DTC, the satellite may implement some proprietary methods to adjust the uplink spectrum, but this needs to be on a UE-by-UE basis. Some additional methods like the one shown in the following figure target an efficiency improvement, as the network may optionally schedule a small guard number of resource blocks (RB) between the uplink PUSCH allocations to fulfil the task of spectrum alignment. For a PUCCH channel, a so-called orthogonal cover code (OCC) is applied to improve efficiency, but in DTC this orthogonality might be impacted and as a consequence, the PUCCH requires more resources.

Figure 8: Uplink resource efficiency, possible impact from Doppler shift

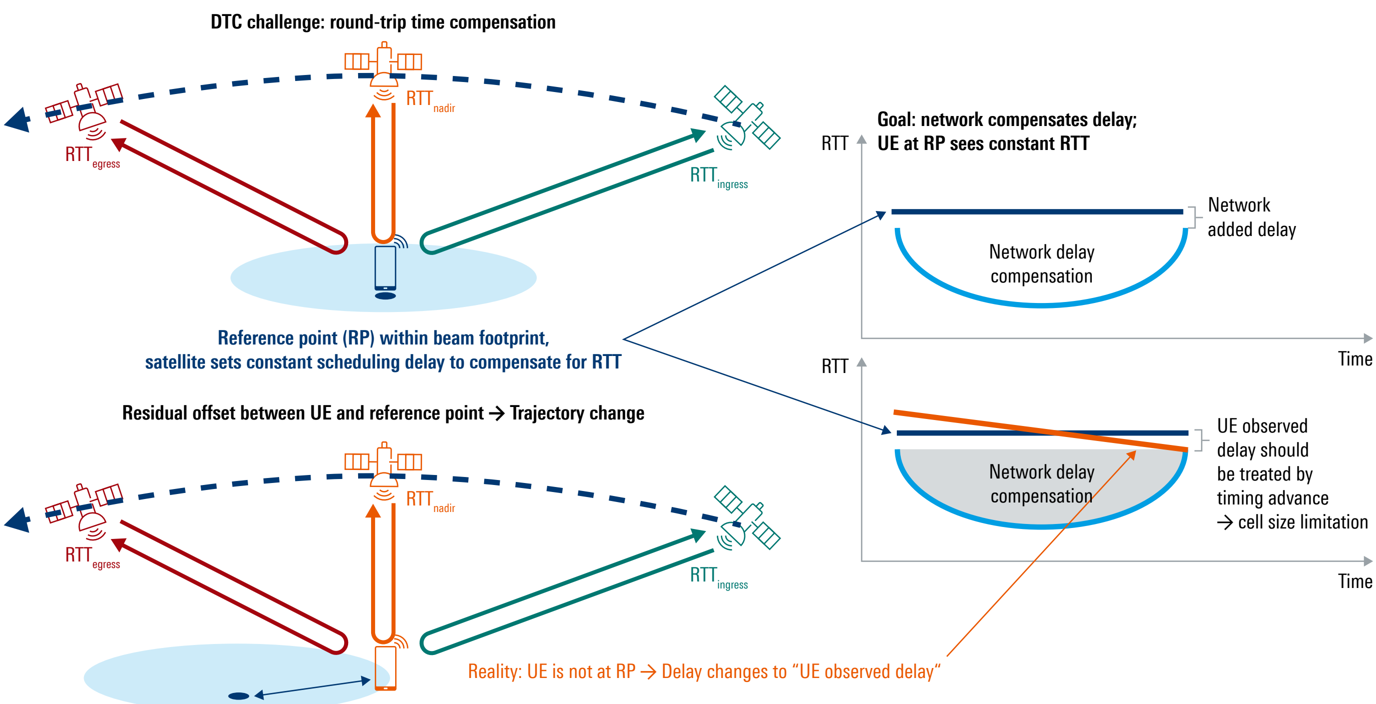


2.5 Round-trip time (RTT) impacting DTC connectivity?

One of the major challenges with NTN is the time delay, which is not only an absolute delay due to the long distance from satellite to earth, but also the time delay is time variant as explained in [Ref. 2]. Note that in DTC situations, the UE does not have any information about the satellite ephemeris and the parabolic shape of the observed RTT during the connection needs to be compensated. In legacy technologies or 5G not modified for NTN as of Rel. 17, the only time adaptation tool is the timing advance method. In LEO constellations, the RTT differs in the range of several milliseconds (e.g. at 600 km orbit, the RTT minimum-maximum difference is around 6 ms), which exceeds the range of timing advance (TA) compensation. Note the parabolic shape of the RTT in Figure 9 and in [Ref. 2].

In terrestrial cases, the maximum amount of TA is given by the cell size. For a maximum cell size of around 100 km radius, the maximum TA is 1280 · 16 · Ts = 2 · 100 km / 300 km/ms = 0.667 ms. Therefore, another tweak applied in DTC means that the satellite will compensate for such RTT. Specifically, the satellite will adapt an additional network delay that emulates the time variant behavior of RTT. From a UE perspective, the delay should be constant. Since the satellite cannot remove the physical delay, it must dynamically add a scheduling delay so that it appears constant. The following figure shows an example where the goal is to transform the parabolic shape of the RTT into a kind of constant line. This can be done by setting up a scheduling delay that is larger than the maximum and minimum RTT. Unfortunately, this time compensation again is only valid for an earth reference point as shown in the upper right part of the figure. Assuming the UE is positioned at the edge of the cell, here the RTT still has a time variant impact (see bent line in lower right part of figure). The deviation versus the constant delay is then in the range of the timing advance adaptation.

Figure 9: Challenge of round-trip time (RTT) flattening

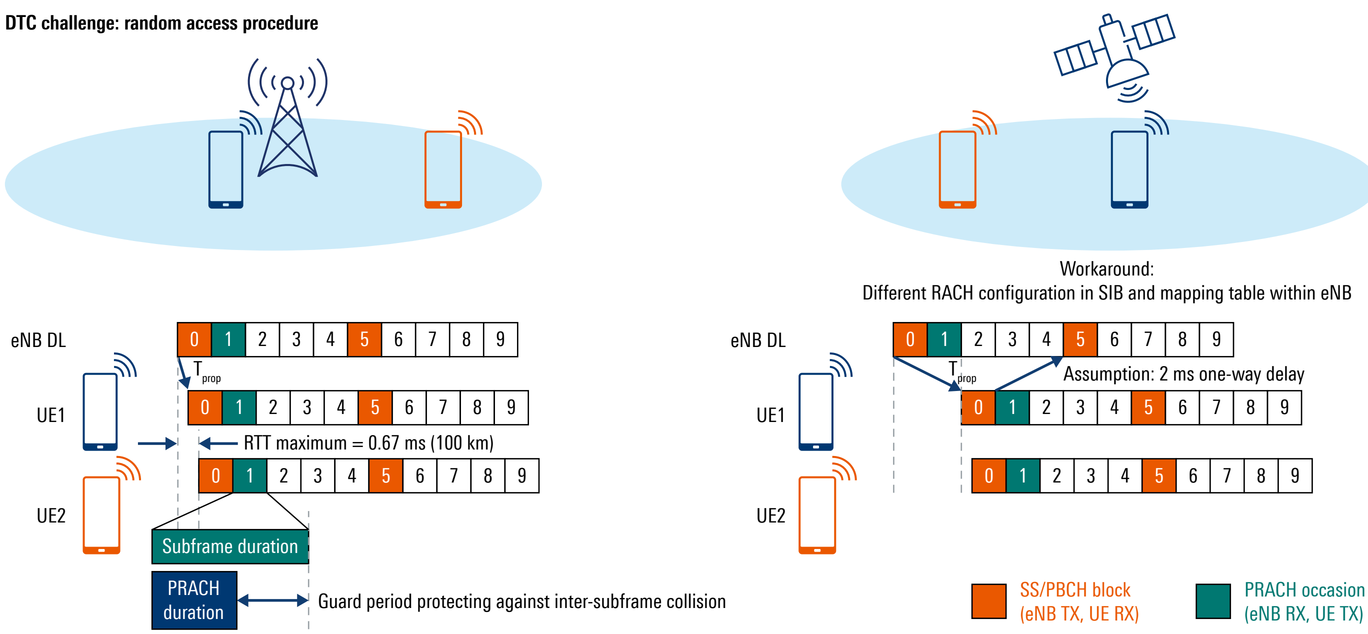


2.6 Random access procedure and timing

One procedure that is affected by the latency in DTC is the random access procedure since there are no additional delay compensation parameters like e.g. 3GPP NTN parameters K_{mac} or K_{offset} (explained in [Ref. 3]). Thus, we have to assume a legacy RACH procedure as specified in EUTRA networks. There are several impacts on the random access because of a certain delay. An overview of mechanisms to counter the random access delay in NTN is given in [Ref. 11]. First, recall the random access procedure in a terrestrial network (see left part of the following figure). There is an individual time offset perceived by each UE, related to the distance to the eNB. The assumption is a cell size within the possible ranges. A PRACH sequence is typically shorter than the duration of a subframe and this guard period will counter against an inter-subframe collision. After the PRACH reception, the eNB can measure and control the UE timing advance and succeeding scheduling uses the full subframe duration. In the right part of the figure, the situation in an NTN scenario is depicted. We assume a one-way latency of 2 ms between the satellite and the UE. Without any modifications, the UE will then transmit the PRACH and this will arrive at an "unwanted" subframe at the eNB. The network signals via system information a RACH occasion (RAO) as an uplink resource in time and frequency that can be used by the UE to transmit a random access preamble. This RAO is also the resource when the eNB expects the PRACH. One possible countermeasure can be that the network will use different RACH occasion (RAO) configuration tables signaled to the UE compared to the RACH occasion tables available internally. Basically, this is "intentional cheating".

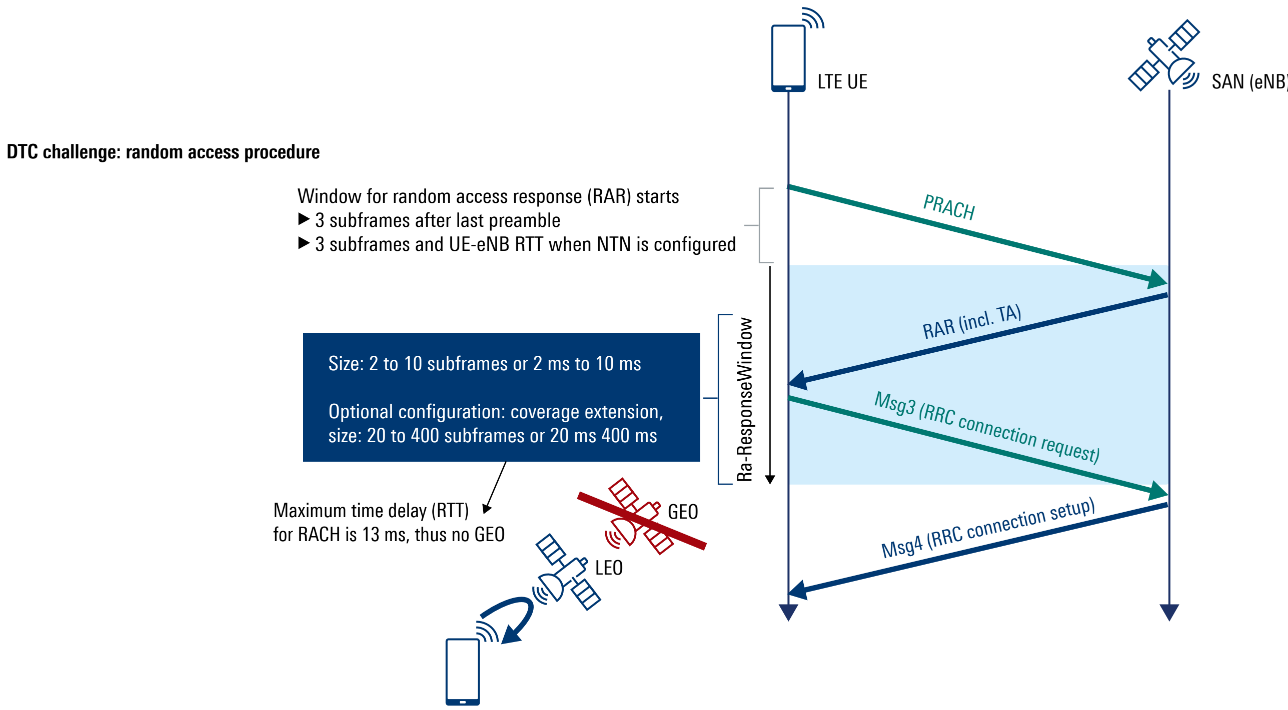
Another possible countermeasure can be a general time offset between the uplink (UL) and downlink (DL) frame structure at the eNB. This is also called subframe-level timing delay (SF-level TD) in the literature [Ref. 11]. In 5G NTN, a similar procedure is possible as shown in [Ref. 2]. However, if applied, it will be signaled as a K_{mac} parameter, whereas in DTC, a possible time offset between uplink and downlink frames is transparent to the UE.

Figure 10: Random access challenges, terrestrial and non-terrestrial networks



Another challenge related to the RACH procedure is the signaling flow and response times affected by the RTT. As shown in the following figure, the UE sends a PRACH preamble as the first message on the random access radio resources, scheduled via system information, in a non-synchronized manner since timing advance might not be preconfigured. The UE now waits for the network message random access response (RAR) to schedule uplink resources and provide an initial timing advance value. This message should be received within a time window of maximum 13 subframes equal to 13 ms, as this is based on LTE technology. As a consequence, we assume that DTC is mostly dedicated to LEO constellations. Note that there is an option for an LTE cell to operate in coverage enhancement mode, but this would entail other challenges.

Figure 11: Random access procedure – legacy and impact for DTC

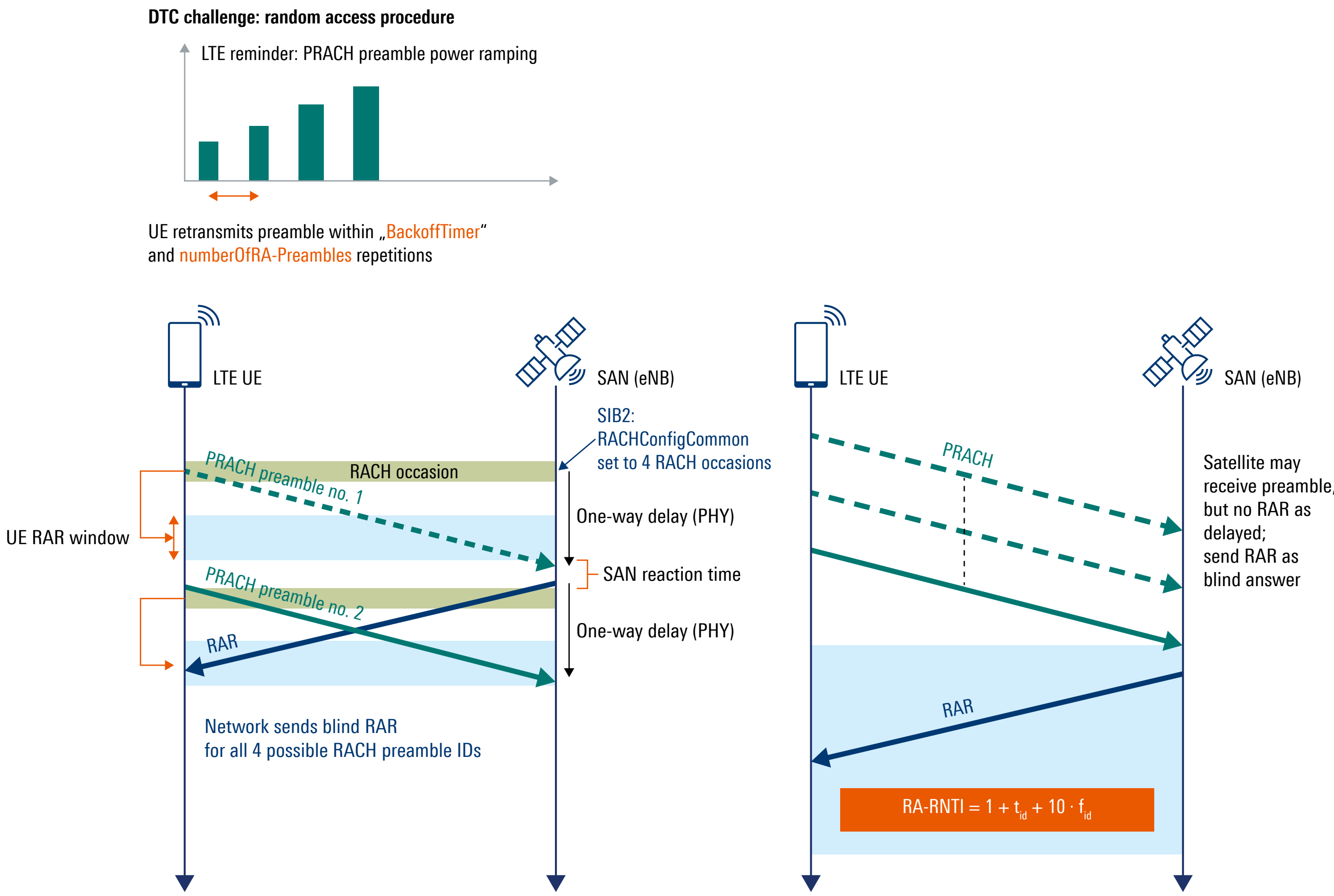


While in 5G NTN parameters have been introduced to defer the RAR response window, DTC does not support any of those protocol layer updates. However, some non-specified workaround may be possible. One configuration scenario suggests a high PRACH config index to maximize the supported cell radius (*prach-ConfigIndex* = 48 and 63). Second, the parameters random access (RA) response window (suggestion sf10) and contention resolution timer (suggestion sf64) should be set to the maximum values to accommodate the delay in LEO constellations.

In LTE, the network can configure the UE to transmit several PRACH preambles via the parameter *numberOfRA-Preambles*, timely separated by the *BackoffTimer* value. Thus, the network ensures that the UE sends multiple PRACH sequences and listens in multiple RAR windows. One suggestion: for *RACH-ConfigCommon* in SIB 2, reduce the number of RA preambles (*numberOfRA-Preambles*) to four, reducing the RACH capacity, but simplifying the blind acknowledgement concept to tackle the delay [Ref. 9].

The tweak might now be a blind acknowledgement where the network sends an acknowledgement before it has received the corresponding PRACH sequence in an estimated time window. This has to be thoroughly configured to avoid mismatches. In LTE, the temporary identity RA-RNTI for the random access response related to the PRACH transmission is calculated according to RA-RNTI = $1 + t_{id} + 10 \cdot f_{id}$, where t_{id} corresponds to the subframe time index of the PRACH transmission and f_{id} to the subcarrier frequency index. In the following figure, an example is depicted. The UE sends PRACH preamble no. 1 and does not get a response in the corresponding RAR window. The network receives preamble no. 1 delayed by the single-way latency. Now the network responds with a blind ACK response for all four possible preambles, as it does not know which preamble the UE has selected for preamble no. 2. By fine tuning the network internal processing time, it can now be achieved that the network RAR falls into the UE RAR window. For NB-IoT or 5G NR, the formula also includes a carrier index and has different multiplication factors; see [Ref. 11].

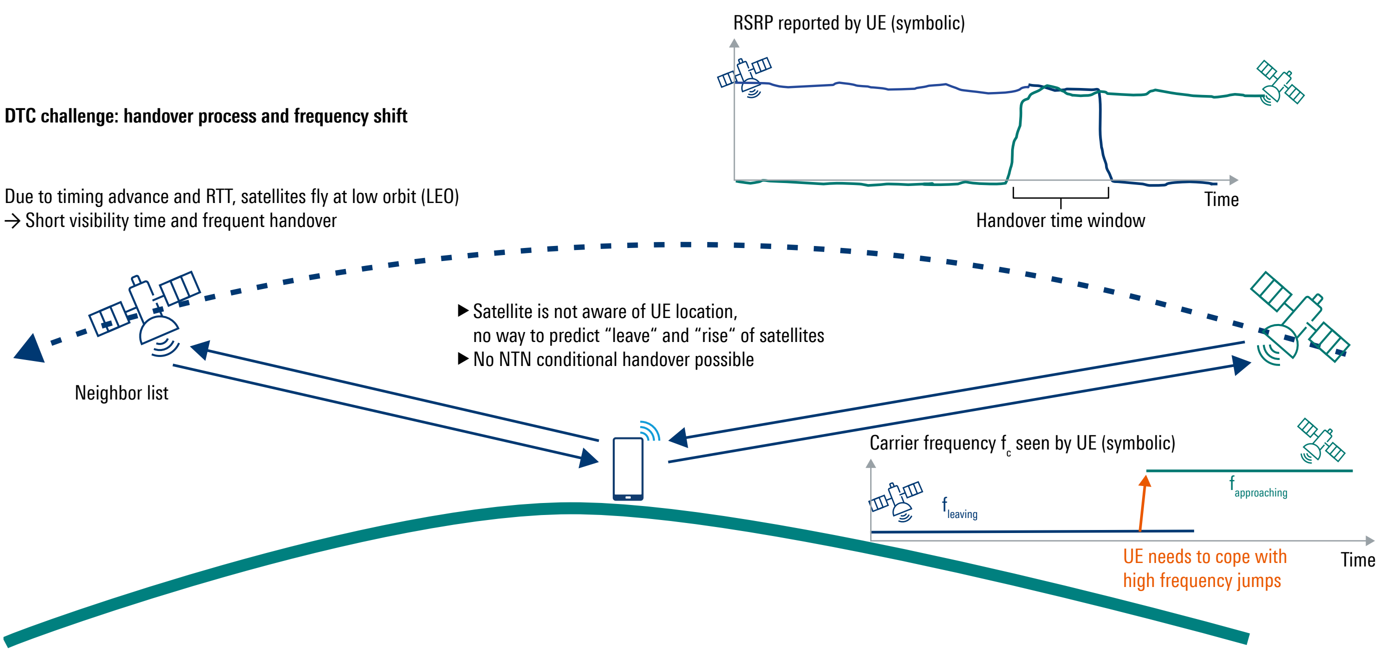
Figure 12: Random access timing aspects – potential workaround to solve latency problem



2.7 Mobility scenarios and handover

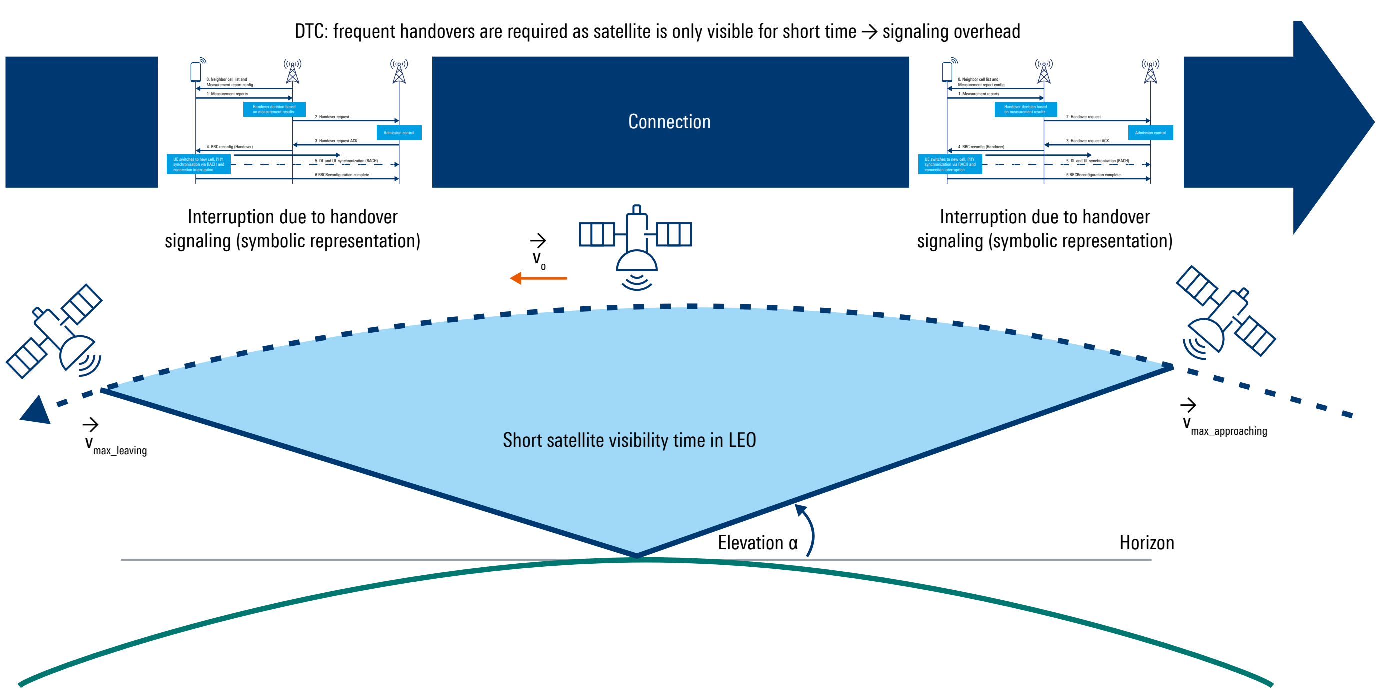
As DTC is most likely based on LEO satellite constellations at a lower orbit altitude, the consequence is a very short visibility of a single LEO satellite. Typical values range from dozen of seconds to minutes, and as a result, frequent handovers occur. The first impact is an efficiency loss due to signaling overhead as the RRC needs to execute the handover procedure at short time intervals. This is shown in a symbolic manner in Figure 14. The second impact is the Doppler shift as the UE might perform handover from a serving satellite that is on the "leaving" path to a target satellite that arrives on the "approaching" path. Such handover includes a change of the carrier frequency as this is affected by the Doppler shift. The network is most likely not aware of the UE location, so it might be difficult to predict the rise and leave status of a satellite, unlike in NR-NTN. Also note that as a third impact, there is no such conditional handover specified for DTC (explained in [Ref. 3]). The baseline handover from EUTRAN is kept as the reference procedure: The UE receives a neighbor list, performs power level (RSRP) measurements and based on the measurement report, the network triggers the handover. In DTC, the challenge is that the RSRP values between leaving and approaching satellites may not differ that much and there is only a very short time window for the handover. Future research might apply some time prediction or blind handover procedures.

Figure 13: DTC handover procedure challenges



To cope with the efficiency issues depicted in the following figure where an abundant signaling overhead due to frequent handovers shrinks the network efficiency, the satellite network might choose a similar solution as defined in 3GPP Rel. 18 for NR-NTN [Ref. 3]. This is a satellite switch with re-sync procedure. The basic idea is to keep the physical cell ID and transfer the cell parameters from the serving satellite to the target satellite to pretend to the UE that no cell change occurs. The drawback is that this requires the satellites to be connected to the same terrestrial gateway and mobility management entity (MME) core network function. This is because there is no additional "interruption" time signaled to the UE, compared to 3GPP Rel. 18 satellite switch with re-sync. In addition, the two satellites need to coordinate their frequency Doppler compensation so that the UE sees both cells with similar carrier frequencies.

Figure 14: Signaling challenge – frequent handovers



2.8 Additional challenges and countermeasures

To ensure the successful operation of DTC satellite networks with acceptable key performance indicators (KPI) regarding end user quality of experience (QoE), some additional tweaks are appropriate and incumbent procedures might be slightly updated. This section presents some of the technical methods that are probably applied in DTC networks. As already mentioned, the satellite constellation should try to behave as an LEO constellation with quasi-earth fixed beam in a multi-beam satellite architecture based on regenerative payload to reduce the latency and tackle the link budget challenge. As the UE is not modified or aware of the cell being a satellite, the network may either try to disable HARQ operation or send blind acknowledgements to avoid a connection stall.

Another possible adaptation, presented in [Ref. 2] for NR-NTN and indicated as $K_{mac,}$ would be a time offset between the uplink and downlink frame structure. Timing advance (TA) controls UL signal reception alignment at the base station. The maximum value in LTE is 1282, as TA signaled in random access response. Hence, a maximum cell size is approx. 100 km for terrestrial LTE cells. In DTC, this corresponds to the maximum distance from satellite to UE. At higher orbits, the trick with the time offset between UL and DL might be mandatory. Unlike NR-NTN, in DTC this optional time offset is not known to the UE and needs to be handled by the network entirely.

LTE supports a hybrid automatic request (HARQ) procedure with a total of eight HARQ processes in each direction, UL and DL. The difference is that the downlink HARQ is asynchronous as the eNB serves multiple UEs and the uplink is synchronous. Downlink related feedback timing in FDD is four subframes, i.e. a UE receiving PDSCH in subframe n will send the A/N feedback in subframe n + k, with k = 4. In TDD, the HARQ follows a configuration index procedure and is much more complex, as A/N bundling might be activated as well, and several timing rules apply (see [TS 36.213] for further details). The typical real network procedure in TN LTE is a closed loop HARQ, i.e. a data packet (PDU) is explicitly acknowledged, and the A/N feedback triggers either new packets or retransmission. The impact with DTC is a longer delay and therefore an impact on the timing of such HARQ processes. The countermeasure is that the network can disable the HARQ operation or operate HARQ in a so-called open loop mode with less stringent retransmission requirements. Disabling HARQ (i.e. ignoring the feedback) is the situation when the network always schedules new data packets. Open loop HARQ operation permits the scheduling of new HARQ process PDU before the A/N is received, scheduling some automatic retransmissions or so-called transmit time interval (TTI) bundling.

HARQ transmission in the uplink is controlled by two configurable parameters: the maximum number of transmissions *maxHARQ-Tx*, and *maxHARQ-Msg3Tx* for a transmission of a MAC PDU stored in the Msg3 buffer, valid for the random access procedure. The recommendation is to set *maxHARQ-Tx* to 1 for communications over satellites with an unmodified UE with no retransmission due to HARQ feedback. If radio conditions are bad, the RRC and MAC layer can adjust MCS or activate TTI bundling to improve link robustness. To counter some delay, the network can schedule the uplink transmission of the PUSCH with a certain delay, covering the RTT (see example in following figure). For the downlink, the eNB controls the HARQ retransmission process and the eNB does not send HARQ retransmissions either. The UE is informed of the new transmission by the eNB toggling the new data indicator (NDI) bit in PDCCH. In addition, the physical layer should set a more robust modulation and coding scheme (MCS). Simulations have shown that the higher layer RLC AM might cope with a BLER of around 5% at the physical layer if the HARQ operation is partially disabled.

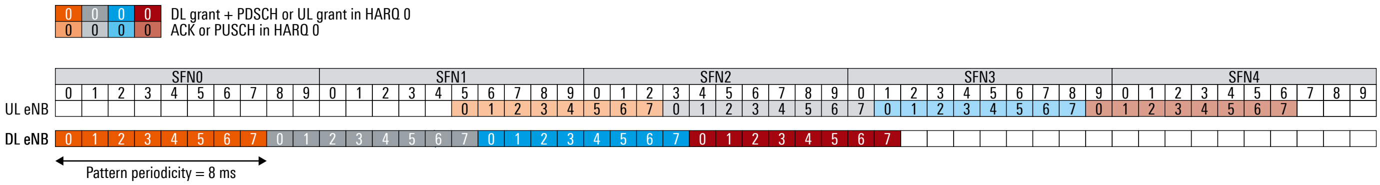
The following figure gives an example of such behavior with open loop HARQ, emulated by a system simulator. We assume an RTT of 8 ms. In the bottom line, the network sends new packets at every TTI and the total number of HARQ processes is eight, as defined in LTE. The UE now sends the corresponding A/N message in the uplink direction four subframes = 4 ms later, plus the assumed RTT of 8 ms and additional 3 ms processing time, which results in a 15 ms overall delay. This has to be taken into account by the system simulator for evaluating metrics like BLER. A real network might either react and retransmit the same data or continue sending new data. Error correction is then left to higher layers like the RLC AM mode.

Our simulation results with different RTT simulations show that the closed loop HARQ compared to the open loop HARQ has only a very marginal impact in a terrestrial network emulation (with high radio link layer SNR). However, the throughput declines recognizably in longer RTT and closed loop HARQ operations as this stalls the transmit window. The long RTT hinders the efficient use of the closed loop HARQ in LTE DTC.

Figure 15: Impact on HARQ operation

Reminder: LTE has 8 HARQ processes in total (UL and DL) = 8 ms cycle.
The ACK/NACK is sent 4 ms after TX of PDSCH and another 4 ms later, the next DCI schedules PDSCH.

Scheduling with retransmission control = DL_HARQ_OPEN_LOOP or UL_HARQ_OPEN_LOOP with 8 ms of channel RTT



Assumption: DTC scenario with 8 ms round-trip-time. The DL DCI for UL PUSCH is sent in SFN0, subframe 0.
The uplink PDU is then sent 4 ms + 8 ms (RTT) + 3 ms = 15 ms later.

Remember that the elevation angle between the satellite and UE contributes to RTT. To combat the latency impact, the network may configure a higher minimum elevation angle for the beam switch procedure. However, this reduces the satellite visibility time and might require more frequent handovers.

2.9 Mobile network operators (MNO) – some impacts

The deployment strategy for DTC is completely left up to the MNO; they will coordinate the subscription profiles and data plans and how to market and provide the satellite connectivity services. Currently, only some services are eligible via DTC and we understand that satellite-based communications is evolving in multiple steps. The North American MNO T-Mobile advertises these services: "T-Satellite supports text messaging, location sharing and now picture messaging and satellite data as devices become eligible. Check the device eligibility list below to see which features your device supports." For details, see their website [Ref. 13]. They indicate a list of UE devices that support DTC and have been tested to work with DTC satellite services.

A similar procedure was introduced in Australia by the operator Telstra, offering satellite-based communications as well. Via their website they also present a list of commercial devices that are recommended for DTC; see [Ref. 18].

With respect to the use cases, DTC might involve a stepwise market approach due to the challenges we have described. Some use cases will be provided by a third party, for example voice calls in DTC are currently based on a specific app that will handle audio coding and packetization. It might have lower QoS performance compared to terrestrial VoNR using IMS as coordinating management.

The satellite network operator SpaceX provides additional information about use cases and services offered by its Starlink satellite network on its website; see [Ref. 12].

Demand for satellite communications is proliferating worldwide. At the present time, multiple negotiations between mobile network operators (MNO) and satellite network operators (SNO) are ongoing. For that reason, we expect updates in terms of the market situation and we believe that DTC will evolve on a quasi-daily basis.

3 TEST & MEASUREMENT ASPECTS

3.1 General aspects for DTC related testing

NTN also represents a paradigm shift from the perspective of test and measurement. This is due to the conditions changing from a setup where the UE is mobile and the network entities are stationary; we now need to consider mobility on both sides. An approach that emphasizes reliable, accurate and reproducible test conditions is still mandatory, thereby necessitating a test setup that is suitably prepared. In addition, as DTC does not correspond to a technology enhancement specified by 3GPP and is based instead on incumbent LTE, no DTC-specific test procedures are available. Some tests originate on the basis of operator-specific requirements since operators have an interest in ensuring that devices and infrastructure entities work together properly. Bilateral communications between the vendor, MNO and SNO and the test equipment manufacturer will help to ensure implementation of the correct test methods.

The change in the radio conditions plays a major role. Unlike existing approaches, the signal weakness or high path loss needs to be considered along with the time delay and the carrier frequency offset known as Doppler shift. In addition to terrestrial fading effects and multipath propagation (MPP), satellite communications is additionally impacted by atmospheric effects like the Faraday effect on polarization, scintillation and weather. Further details are explained in [Ref. 5] and in [Ref. 2]. The 3GPP study in [TR 38.811] also gives an excellent overview of channel scenarios and specified channel models for 5G NTN that can be reused for DTC testing.

3.1.1 Software-assisted testing

One common trend in wireless communications is the emphasis on software-assisted testing routines or software snippets that are also used for test purposes. As DTC is not standardized and requires some tweaks and workarounds in the network configuration, test equipment that allows flexible configuration is highly beneficial.

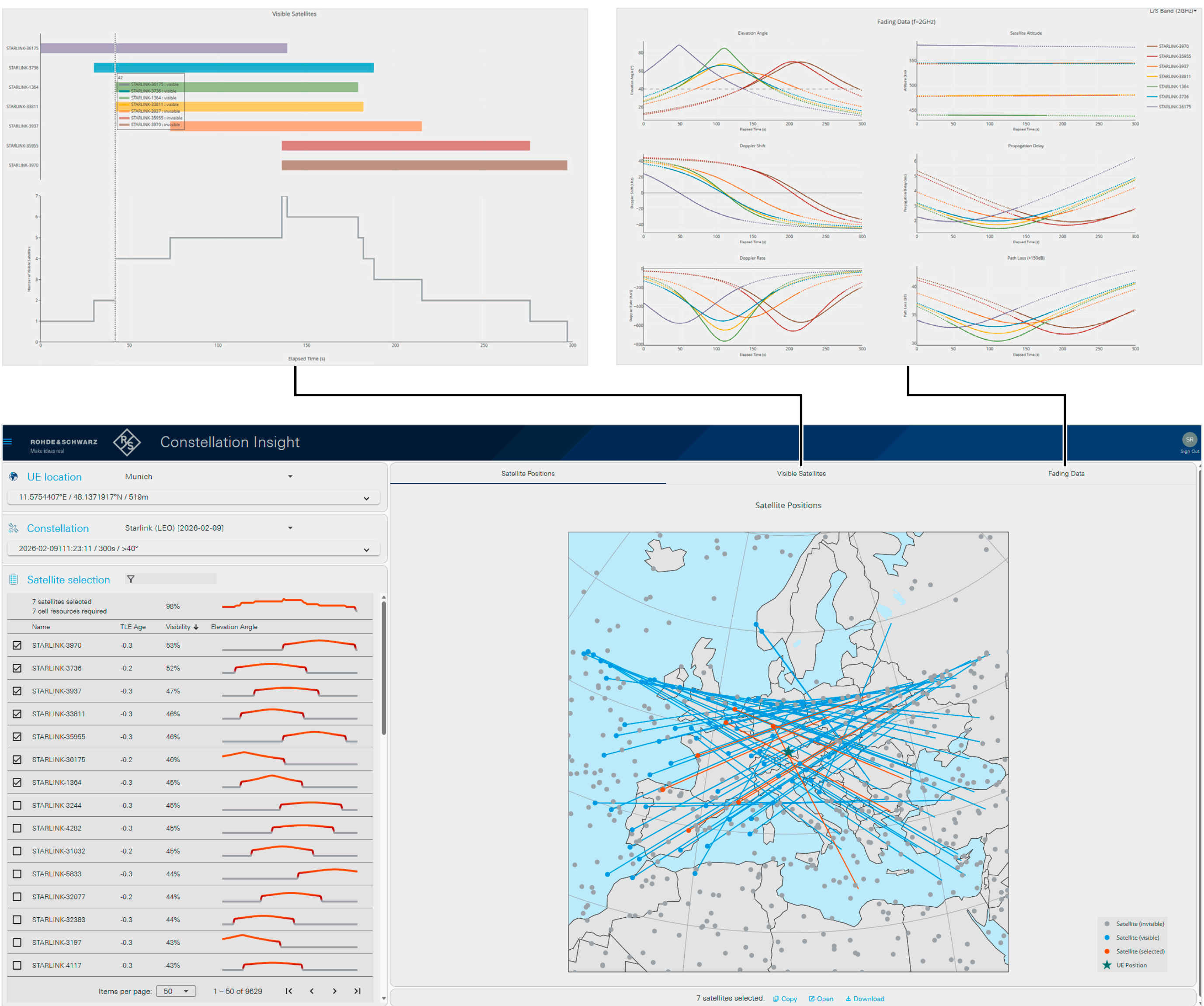
The **CMX500 radio communication tester** supports another important feature in the context of software-assisted testing, i.e. the capability to automate the test system. We will not go into the details of test automation or remote scripting, etc. However, related to DTC testing, one important aspect to be considered is the dynamic nature of the satellite constellation, i.e. satellites travel at high velocity, which makes manual configuration of the network too slow. Within the mobile radio tester, an auto-deployment and auto-handover software routine automates the bringing of satellite cells online and transfers connections seamlessly as satellites move in and out of visibility. With this feature, control software uses the configured constellation of satellites and emulates those satellites that are visible. It also triggers mobility procedures when the visibility loses track or handover conditions should be triggered. This feature is needed as the hardware of the CMX500 is limited to a maximum number of cells that can be activated simultaneously (currently, a maximum of six cells is possible in one box). This enables the user to perform testing in the context of highly robust long-term operations.

The entire testing process can be fully automated through the powerful XLAPI Python interface, while the optional AI-powered **ScriptAssist** tool improves the speed and effectiveness when creating dependable automation scripts [Ref. 3]. Scripting is essential for automation, enabling the creation of new scripts, updating existing ones, and providing detailed explanations of scripts. An innovative solution leverages natural language processing and machine learning to automate test script generation and 5G functional tests, streamline workflows, accelerate product launches, and ensure comprehensive test coverage.

Constellation Insight software tool for constellation planning and NTN UE testing

As an example to showcase the aspect of software-assisted testing, we will now consider a user who wants to configure a satellite constellation for satellite emulation in order to test a UE under such conditions. This is a new paradigm compared to terrestrial networks where the cells are more static. To enable the highest degree of flexibility, Rohde&Schwarz developed the **Constellation Insight** software tool that permits the user to load existing satellite constellations or to configure user-specific constellations. The following figure shows such an example where we have configured our UE to be in Munich, Germany and we have chosen the satellite constellation Starlink from SpaceX. The left part shows the possible satellites that should be in range and on the right side, we can see the satellites and their flight paths. Two additional screenshots are inserted for graphical purposes only. One of them shows the satellite visibility over time and the other shows calculated RF characteristics like delay, Doppler shift and path loss. The idea is that the user can configure a definable test scenario, i.e. even a custom scenario is possible where the user can configure proprietary satellite constellations. Via a download button, it is possible to generate a configuration file that can be loaded into the CMX500 as a Python script to run such a satellite scenario under live conditions, with real emulated satellite-based cells accordingly.

Figure 16: Constellation Insight software-assisted planning tool for satellite constellations emulated with the CMX500

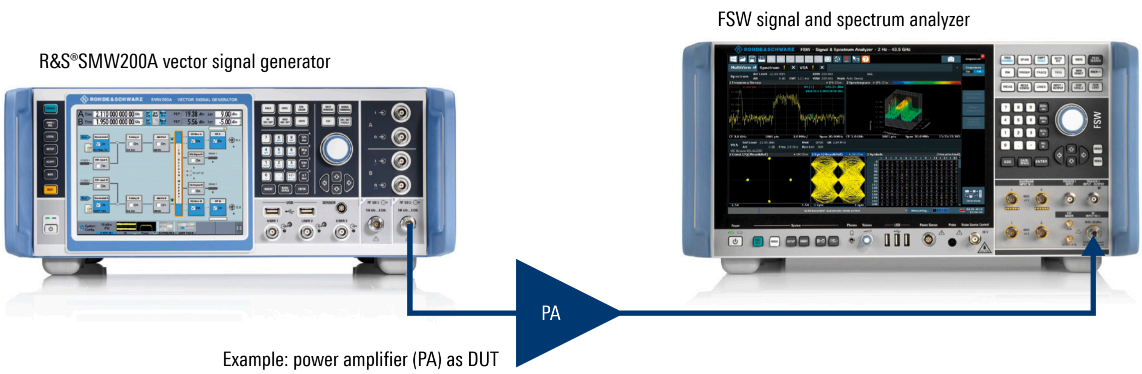


3.2 Infrastructure supporting DTC – testing aspects

We are including this section for the sake of completeness, but note that currently, no direct DTC infrastructure test scenarios are defined. The satellite base station needs to fulfill the 3GPP base station RF testing requirements in [TS 36.141].

In the following figure, a standard test setup for satellites with two generic test instruments is depicted. The test uses a signal generator, for example the **R&S®SMW200A vector signal generator**, and a signal analyzer, for example the **FSW signal and spectrum analyzer**.

Figure 17: Test setup for satellites and components for DTC with R&S®SMW200A and FSW



The R&S®SMW200A vector signal generator covers frequency ranges up to 67 GHz without additional converters and supports two channels with each having a modulation bandwidth of 2 GHz. The hardware is based on a modular concept consisting of various hardware and software options, making this instrument a flexible, multi-purpose test tool. With respect to fading, the signal generator can be equipped with an internal baseband fading emulator, offering the ability to emulate fading in a one-box approach with a single user interface in a cost-efficient manner. The fading concept includes various multi-antenna configurations (SISO, MIMO, TX diversity, etc.), carrier aggregation and dual connectivity scenarios, and standard fading profiles (e.g. ITU and 3GPP profiles). Moreover, it allows configuration of a user-specific fading profile where the user can configure multiple delay taps, power settings and phase and time offsets as well as Doppler shift individually.

With the FSW signal and spectrum analyzer, Rohde & Schwarz offers a sophisticated and powerful signal analyzer, covering frequency ranges up to 90 GHz without the need for an additional frontend and supporting a bandwidth of up to 8 GHz. Various hardware and software options make this instrument a flexible and powerful tool, fulfilling the need for DTC testing. The tests include legacy test methods for satellite payload testing, e.g. spectrum emissions and spectrum mask, ACLR, OFDMA signal modulation performance, DVB-S2X signal modulation performance, group delay, EVM, gain compression and gain transfer for amplifier testing, noise power ratio (NPR) and possibly a customized menu to analyze proprietary waveforms.

Further details and product documents are available via Rohde & Schwarz representatives or via our website [Ref. 14].

3.3 UE testing aspects related to DTC

DTC key testing categories for UEs include radio frequency (RF) testing, protocol testing, performance testing, carrier acceptance testing and interoperability testing, but related to existing 3GPP specifications for LTE and in addition based on satellite network operator specific requirements.

The major advantage of the solutions provided by Rohde & Schwarz is that they support multiple technologies with the same instruments, i.e. IoT-NTN, NR-NTN and DTC can be performed with the CMX500 radio communication tester.

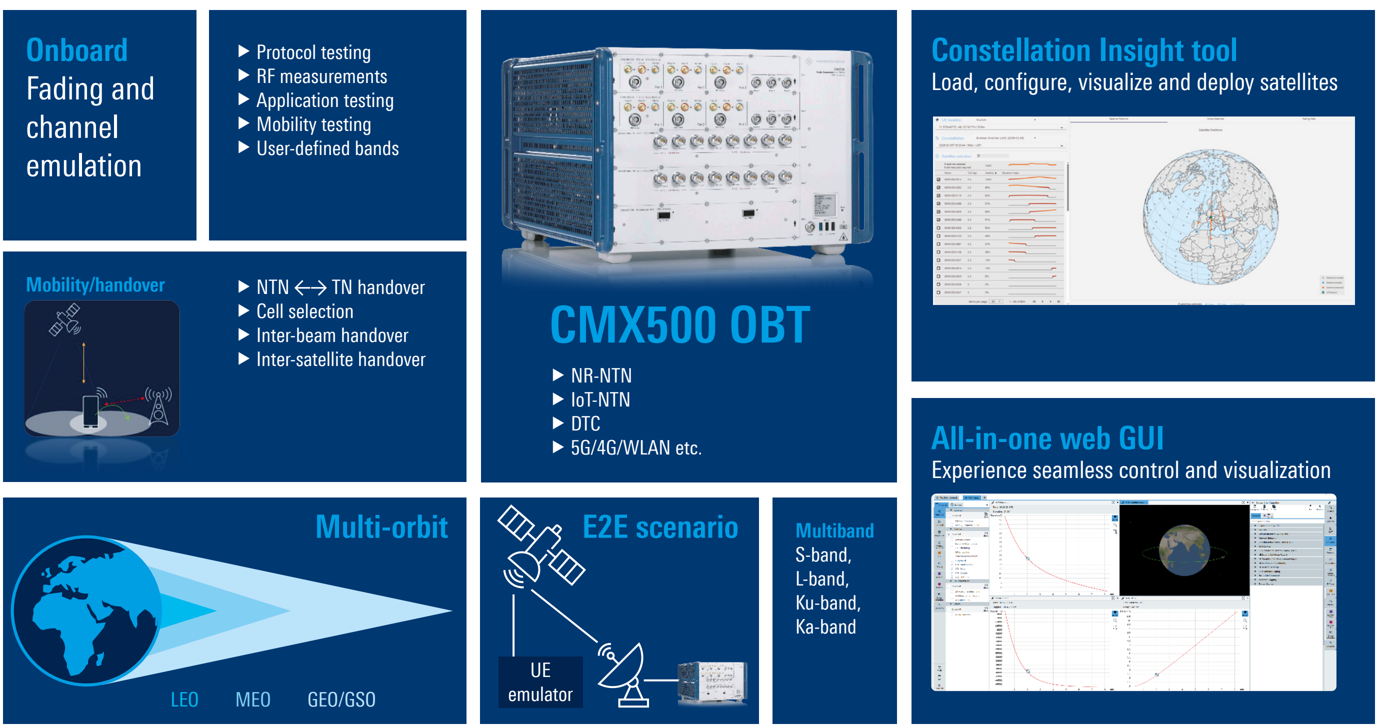
3.3.1 DTC UE test solutions: CMX500

Rohde & Schwarz provides a powerful test solution for UE NTN testing with its CMX500 radio communication tester. The CMX500 emulates DTC cells, 5G NTN cells as well as terrestrial network (TN) cells in frequency ranges FR1 and FR2, as well as future FR3 regions. It represents a very flexible modular platform that can be equipped with various hardware entities like a signaling unit or frontend. Moreover, a wide range of software options are available, enabling support for multiple radio technologies like 5G, 5G NTN, LTE, WLAN – to name only the most important examples. With the CMX500, the user can perform tests from RF via protocol and signaling up to E2E application testing.

The CMX500 one-box tester (OBT) is the versatile solution designed for testing various NTN technologies, including NR-NTN, NB-NTN and DTC, all conveniently housed in a single unit. It provides multiband and multiorbital support, along with a dedicated NTN workspace that enables users to visualize the deployed network and its relevant parameters.

Details about the test solution and its capabilities are provided in [Ref. 15].

Figure 18: CMX500 platform for UE NTN testing

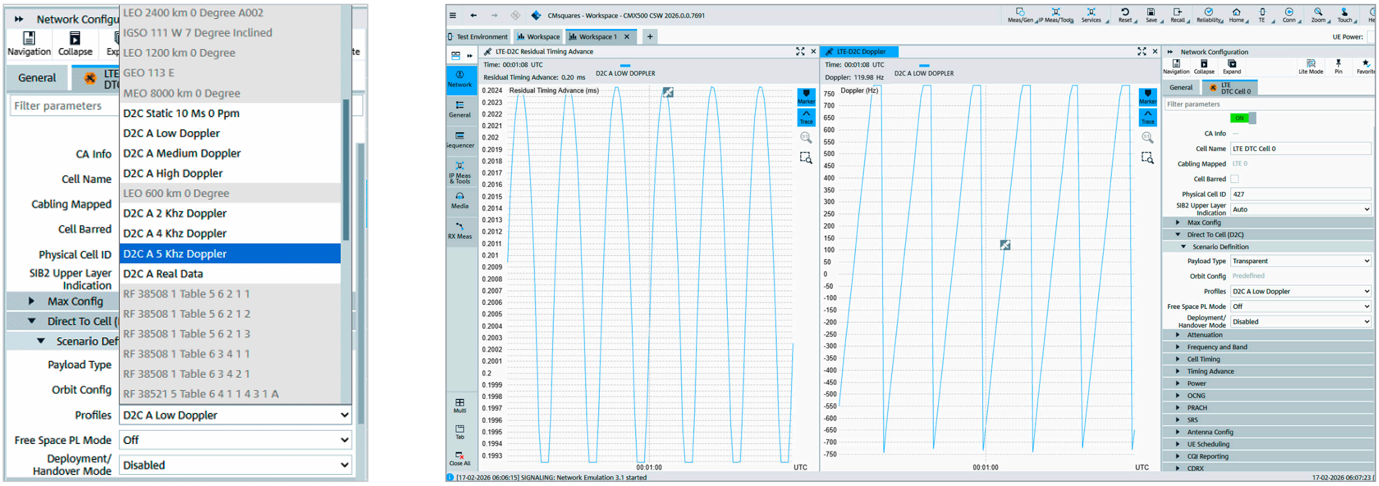


The user can configure custom settings in the cell configuration, for example a DL-UL frame timing offset of several milliseconds or a change of relevant layer 3 messages via a powerful message composer tool. Moreover, like NR-NTN, the CMX500 supports internal fading via an internal channel emulator that can be activated for DTC testing as well.

The following figure shows a screenshot of such DTC related measurements. Via a menu in the GUI, the user can select pre-configured Doppler shift scenarios for DTC and test the residual timing advance and Doppler frequency.

Figure 19: DTC related testing with CMX500 to configure and test Doppler shift and timing advance

CMX500 GUI supporting internal fading and Doppler emulation for direct-to-cell measurements



To enable the highest degree of flexibility for the user, besides a graphical user interface (GUI) and remote control functionality, the CMX500 supports a Python-based scripting tool (XLAPI) to allow the user to create proprietary test sequences and procedures. In addition, Rohde & Schwarz provides relevant test cases via software options. For example, the R&S®CMX-KF655X XLAPI test package contains purpose-built LTE D2C testing scenarios that are validated in collaboration with SpaceX. Moreover, future packages are on the roadmap to support other satellite constellations, like e.g. AST SpaceMobile.

For example, in current test packages for DTC, the following scenarios are analyzed and verified:

- ▶ Low Doppler delay, medium Doppler delay, high Doppler delay
- ▶ Time offset between uplink and downlink frames of several milliseconds
- ▶ Attach time and attach success rate while the system simulator is on LTE DTC mode
- ▶ Event A3 handover scenario between intra-frequency LTE DTC cells
- ▶ Cell reselection between intra-frequency LTE DTC cells
- ▶ Frequency tracking error measurement on LTE DTC cell
- ▶ Recovery of the connection after radio link failure on LTE DTC cell

These test procedures for DTC can be combined with test procedures for NR-NTN, IoT-NTN or with incumbent type approval and certification testing for LTE and 5G [Ref. 15]

3.4 Phased array testing aspects

This section cannot replace the wide-ranging literature that is available on the topic of antenna testing and over-the-air (OTA) testing. However, the reader should keep in mind that DTC satellites apply directive antennas and beamforming methods that need to be evaluated by such test methods.

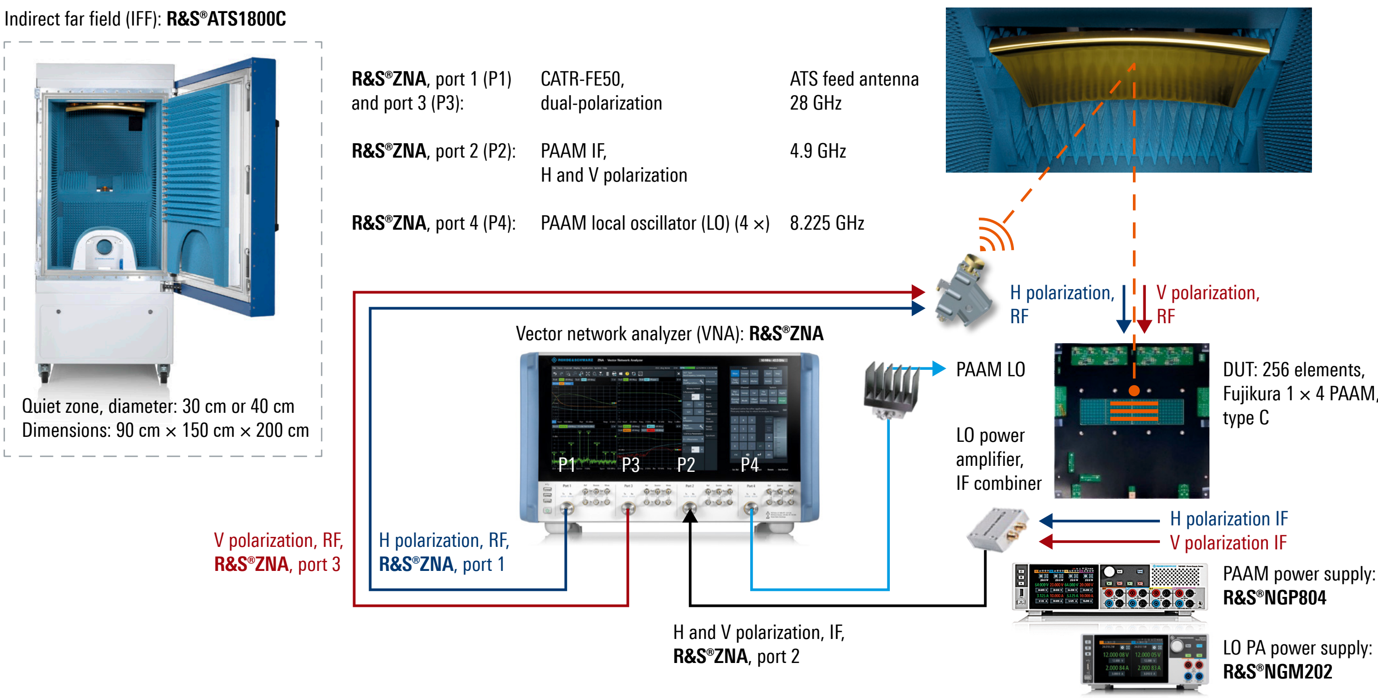
Electronically steered array (ESA) antenna and phased array antenna modules (PAAM): We should first recall the general architecture of an antenna array that enables a directive antenna. Such antennas have multiple antenna elements spaced in an aperture size. By injecting the signal into each element with a different phase shift, we can steer the radiation direction. There are various categories for beamforming arrays: analog beamforming, digital beamforming or hybrid beamforming. Recalling from the laws of physics that phase shifts are frequency dependent, we know that a PAAM can be used efficiently for narrowband signals, but when wide bandwidth is required, we can steer the beam with time delay instead of phase shifters in order to overcome the frequency dependency. Since phased array antennas steer beams without physically moving the array, the line of sight between the antenna and its counterpart (e.g. gateway and satellite) is often not normal to the plane of the array. This means that the effective area of the antenna is reduced, as only a projection of the full area is exposed. This creates a scan loss, reducing the overall gain of the antenna.

Phased array antenna module (PAAM) testing aspects

The above-described parameters and challenges of antenna arrays and beamforming methods require sophisticated test approaches. Electronically steered array (ESA) antennas are regarded as a pivotal technology for satellite terminals in emerging constellations and the integration of NTN with terrestrial communications systems. Their advantages include beamforming and beam steering capabilities, which enable seamless handovers between fast-moving satellites, as well as support for multiple beams, facilitating multi-orbit operations. In addition, an ESA exhibits a faster tracking speed and a faster beam switching time, is lightweight and has no moving parts. Rohde & Schwarz is offering and exploring the latest advancements in phased array antenna technologies while proposing test solutions for verifying their critical performance parameters. For further details and additional PAAM test setups, see [Ref. 3] and [Ref. 16].

Figure 20: Indirect far field (IFF) testing of PAAM

2D/3D RX beam pattern, calibration verification, EIRP, ND, G/T and circular polarization axial ratio



3.5 Mobile network testing (MNT) evaluating DTC connectivity

Mobile network testing complements the wide area of wireless communications testing fields and applications and covers various aspects of field testing to evaluate the performance of mobile networks. A description of MNT test solutions and further information on various applications can be found in the reference [Ref. 17]. The existing test solutions for mobile network testing support DTC network evaluation. One major motivation for DTC is to improve the overall coverage by complementing terrestrial networks with satellite connectivity, worldwide. This can be verified with MNT test solutions like a mobile network scanner, e.g. the **R&S®TSMx**. Advantages of a scanner instead of a test UE is the wider frequency range, much higher accuracy and the scanning speed. While a UE only monitors the frequency channels provided by neighbor list info, a scanner can monitor the entire spectrum range based on its capabilities and detect missing handover relationships or identify unwanted interfering signals. As DTC is tied to spectrum allocations on a national basis, but might provide radio coverage cross-borders, governmental regulators or network operators may use scanners to verify proper frequency usage.

Like in terrestrial testing for MNT, we classify the test methods into passive and active testing. A scanner performs passive testing, as it only monitors the downlink spectrum, i.e. no connection is established and therefore no USIM or network subscription is required. The major difference between a scanner and a spectrum analyzer is that the scanner is designed specifically for mobile communications standards like e.g. EUTRAN, 5G NR or NB-IoT and can decode the system information blocks to perform initial functional tests and check if the network is available. The passive testing method used by a scanner can be extended by a test UE for active testing or testing in connected mode. The QualiPoc Android tool is based on a commercial smartphone architecture, but with full access to the UE's baseband chipset information. This is an important aspect for troubleshooting scenarios, as the user can read the message logs with all details to identify any mismatches that caused a connection disturbance.

Typically, MNT test metrics for DTC are:

- Coverage related RF metrics like RSRP, RSRQ, RS-SINR or RSSI, including serving satellites but also neighbor satellites and terrestrial cells
- Spectrum clearance verification as general spectrum scan in the relevant frequency region to check if any unwanted spectrum occupation has occurred
- QoS of the E2E connection or interactivity testing, including RTT determination, packet loss or BLER, packet delay variation and throughput, measured as peak and average
- Mobility verification: tracking area updates and cell or PLMN selection and re-selection up to handover success ratio determination
- Physical layer related procedures like the random access success ratio or SIB decoding. When the network configures additional coverage enhancement methods like packet repetitions, they can be detected and verified by MNT testing
- E2E or application QoE, e.g. the audio quality in a voice call or video call, the success ratio of SMS transfer as well as delay and throughput on the application layer

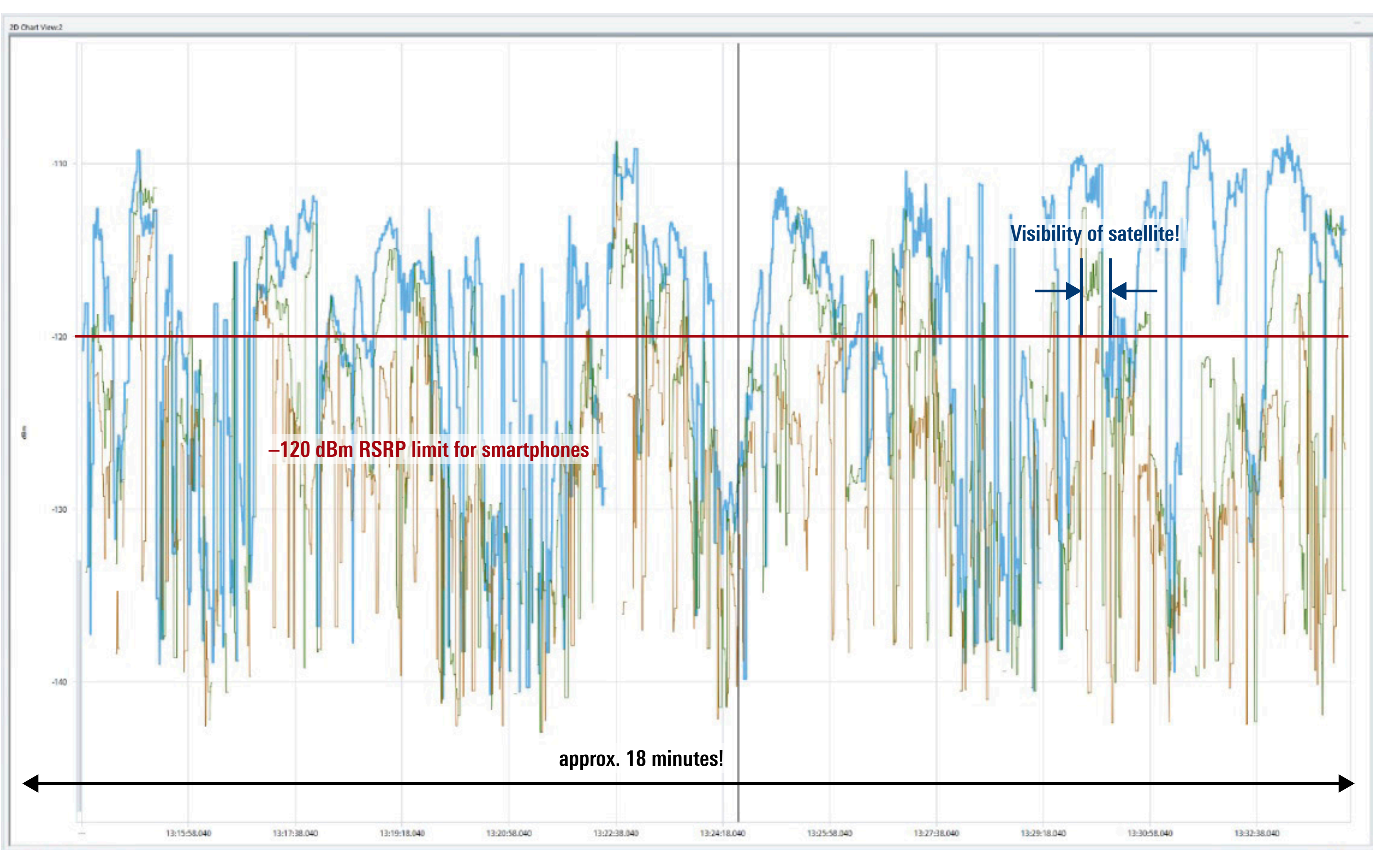
The following figure contains an exemplary screenshot taken during a field test performed in the context of DTC.

The test was performed in a rural area in Montana, USA scanning the SpaceX Starlink DTC LTE network. During the scan period of about 18 minutes, about 100 satellites were identified and the analysis software shows the best three cells as a separate line. It is obvious that for most of the time, the satellite network fulfils the coverage requirements. But as explained in section "3.7 Mobility scenarios and handover", it is also shown that a single satellite has a very short visibility time and frequent handovers must occur to maintain the connection.

Figure 21: Mobile network testing example for DTC

SpaceX Starlink (DTC LEO) in Montana, USA (2025)

- 100 satellites received
- Best three DTC cells highlighted in analysis tool



4 SUMMARY

The goal of providing seamless internet connectivity across the entire globe based on a resilient network is gaining further momentum in the industry. While standardization via 3GPP is accelerating the pace by introducing several technological aspects into its releases, the idea of provisioning LTE connectivity via a cell tower in space represents an earlier time-to-market approach that is enabling use cases and services to complement the legacy terrestrial networks. On one hand, DTC faces several challenges that might impact the overall system efficiency. On the other hand, the techniques introduced reveal the flexibility of LTE technology and show that sophisticated methods can counter such challenges to achieve the goal of satellite-based connectivity faster and help the industry to work on future use cases.

Leading industry players from the wireless and aerospace ecosystem are driving these ideas, supported by tier 1 mobile network operators who want to extend their capabilities by offering additional services. Initial results show that DTC is working properly, which will help to foster the evolution towards a 6G unified network. We can consider DTC as an interim technology on the long path towards ubiquitous coverage. However, the fact that it works with unmodified, commercially available end user devices will definitely help to enhance the community of subscribers using satellite-based connectivity services and elaborate on future use cases. The fact that the UE is unmodified does not ensure that every device works properly in DTC networks. Test and measurement solutions help verify UE performance in such situations. A major drawback remains in the form of spectrum allocation: Supplementary spectrum based on satellite spectrum sharing methods and allocation of MSS spectrum for DTC is limited to nationally confined regions. Nevertheless, coexistence aspects can be identified and solved to trailblaze the path for NR-NTN with internationally regulated spectrum allocations.

At Rohde & Schwarz, we understand DTC as a complementary technology to the existing wireless communications technologies, and we will support the industry ecosystem with test and measurement solutions that enable users to verify their DTC and their 5G NTN DUTs. As there are no standards specifying test methods for DTC, it is essential for us to stay in close contact with the leading industry players and support them with sophisticated test solutions. We do not understand DTC as an isolated technology evolution. For us, DTC belongs to the ecosystem of satellite communications and we are dedicated to helping this evolution along its further path. Of course, we are very proud to contribute to the community with our test solutions for satellite communications.

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Note: All links have been checked and were functional when this document was created.
However, we cannot rule out subsequent changes to the links in the reference list.

6 ABBREVIATIONS

Term	Explanation
3GPP	3rd generation partnership program
5GC	5G core network
5GS	5G system
ACK	Acknowledgement
ACLR	Adjacent channel leakage ratio
AI	Artificial intelligence
AM	Acknowledged mode
AMF	Access and mobility management function
AWS	Advanced wireless services
BLER	Block error rate
CEPT	Conférence Européenne des Administrations des Postes et des Télécommunications (i.e. European Conference of Postal and Telecommunications Administrations)
CFO	Carrier frequency offset
CN	Core network
CP	Control plane
D2D	Direct-to-device
D2H	Direct to handheld
DCI	Downlink control indicator
DL	Downlink
DTC	Direct-to-cell
DUT	Device under test
DVB-S2X	Digital video broadcast over satellite
E2E	End-to-end
eMBB	enhanced Mobile broadband
eNB	evolved NodeB (LTE base station)
EIRP	Equivalent isotropic radiated power
EPC	Evolved packet core (LTE core network)
ESA	Electronic steered array
EUTRA	Evolved UMTS terrestrial radio (LTE air interface)
EUTRAN	Evolved UMTS terrestrial radio access network
EVM	Error vector magnitude
FCC	Federal Communications Commission
FDD	Frequency division duplex
FR	Frequency range
FSS	Fixed satellite services
GCF	Global Certification Forum
GEO	Geostationary earth orbit
gNB	next generation NodeB (5G base station)
GUI	Graphical user interface
HARQ	Hybrid automatic repeat request
HPLN	Home PLMN
HSS	Home subscriber services
ID	Identity
IE	Information element
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IMS	IP multimedia subsystem
IMT	International Mobile Telecommunications
IoT	Internet of things
IoT-NTN	IoT over non-terrestrial networks
IP	Internet protocol
ISL	Inter-satellite link

Term	Explanation
ITU	International Telecommunication Union
KPI	Key performance indicator
LEO	Low earth orbit
LTE	Long-term Evolution (4th Generation)
LTM	Layer 1/layer 2 triggered mobility
MAC	Medium access control
MCS	Modulation and coding schemes
MME	Mobility management entity
mMTC	Massive machine type communications
MNO	Mobile network operator
MNT	Mobile network testing
MPP	Multipath propagation
MSS	Mobile satellite services
NAS	Non-access stratum
NB-IoT	Narrowband internet of things
NDI	New data indicator
NodeB	Term for base station
NPR	Noise-power ratio
NR	New radio
NR-NTN	New radio NTN
NTN	Non-terrestrial networks
OCC	Orthogonal cover code
OFDMA	Orthogonal frequency division multiple access
PAAM	Phased array antenna modules
PCF	Policy control function
PCRF	Policy and charging rules function
PTCRB	PCS Type Certification Review Board (abbreviation no longer used in this way, see: www.ptcrb.com)
PDCCH	Physical downlink control channel
PDSCH	Physical downlink shared channel
PDU	Packet data unit
PGW	Packet gateway
PLMN	Public land mobile network
PPDR	Public protection disaster relief
PRACH	Physical random access channel
PUCCH	Physical uplink control channel
PUSCH	Physical uplink shared channel
QoS	Quality of service
QoE	Quality of experience
RACH	Random access channel
RAO	Random access occasion
RAR	Random access response
RA-RNTI	Random access RNTI
RAT	Radio access technology
RAN	Radio access network
RB	Resource block
RF	Radio frequency
RLC	Radio link control
RNTI	Radio network transaction identity
RP	Reference point
RRC	Radio resource control
RSRP	Reference signal received power
RSRQ	Reference signal received quality
RSSI	Received signal strength indicator
RTT	Round-trip time

Term	Explanation
RX	Reception
SAN	Satellite access node
SCS	Subcarrier spacing
SFN	System frame number
SGW	Serving gateway
SIB	System information block
SIM	Subscriber identity module
SMS	Short message service
SNO	Satellite network operator
SNR	Signal-to-noise ratio
TA	Timing advance
TDD	Time division duplex
TN	Terrestrial network
TTI	Transmit time interval
TX	Transmission
UE	User equipment
UL	Uplink
UM	Unacknowledged mode
UPF	User plane function
USIM	UMTS subscriber identity module
VoNR	Voice over NR
VPLMN	Visited PLMN
VSAT	Very small aperture terminals
WLAN	Wireless local area network

Rohde & Schwarz

The Rohde & Schwarz technology group is among the trailblazers when it comes to paving the way for a safer and connected world with its leading solutions in test & measurement, technology systems and networks & cybersecurity. Founded more than 90 years ago, the group is a reliable partner for industry and government customers around the globe. The independent company is headquartered in Munich, Germany and has an extensive sales and service network with locations in more than 70 countries.

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