# Convergence of the Telecommunication systems with 5G and 6G

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One observe a profound evolution in the communication networks towards the convergence of access technologies. The integration of satellite access with terrestrial mobile networks is enabled by the 3GPP Non-Terrestrial Network (NTN). The satellite network component can contribute to the global service continuity and resiliency of mobile systems. Leveraging the terrestrial 5G access technology, a number of solutions mitigating the issues inherent from satellite communications specifics (e.g. Doppler, delay…) have been standardized in Rel-17 of 3GPP under the so called NTN (Non-Terrestrial Network) standard. In the 5G-Advanced (starting from Rel-18), further NTN added value will be unleashed by the usage of regenerative payload architecture and performance optimization enablers. In the ITU IMT-2030's vision, the 6G will bring new network capabilities to support the interactions between the human and its physical environment leveraging real time digital modelling. In particular 6G will see the unification of the TN and NTN into a multi-dimensional architecture enabled by a set of innovative technologies and concept at both radio and network levels.

## INTRODUCTION

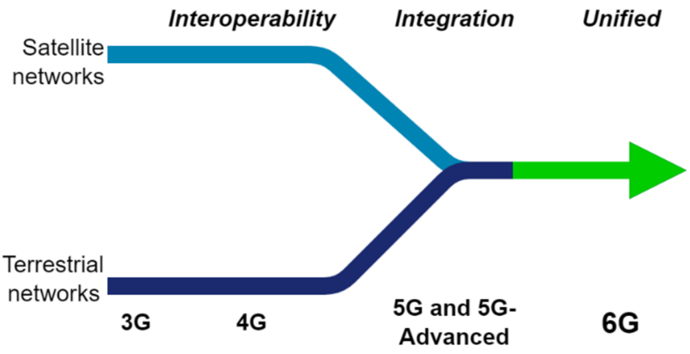

Figure 1: TN and NTN convergence towards a unified access network.

For decades, the mobile communications technologies for terrestrial and non-terrestrial (Satcom) evolved apart from each other. Satellite backhauling was used in first 2G networks e.g. to connect the BTS and BSC via A-bis interface over satellite and network interoperability in 4G. There are mainly two categories of use cases for NTN: 1) Service Ubiquity: This is related to global connectivity and reducing digital divide by providing direct access connectivity for Handset and IoT devices in remote unserved or underserved geographical areas. With such use cases, NTN in 5G offers a complementing role to Terrestrial Network (TN) access. 2) Global service continuity and resiliency: Use cases where 5G services cannot be offered by terrestrial networks alone.

A combination of TN & NTN provides service continuity for such use scenario, higher reliability/availability: as example of such use case you can think about moving platform mounted devices, and aircraft mounted devices.

The 5G technology going forward with a seamless integration of Terrestrial Network (TN) and Non-Terrestrial Network (NTN) segment, including satellites and High Altitude Platform Station (HAPS). In order to support such hybrid terrestrial-satellite systems enabling New Radio (NR) and Internet of Things (IoT) though satellites, the 3GPP starts in Rel-15[1] (2018) and Rel-16[2] (2020) studying issues posed by NTN for an integration to the existing terrestrial-based 3GPP mobile technology. The necessary features for the support of this NTN component have been specified as part of the 3GPP Rel-17[3].The Rel-17 normative works on NTN in 3GPP Technical Specification Group (TSG) on Radio Access Networks (RAN) and Service & Systems Aspects (SA) have been completed in June 2022 while the ASN.1 freeze was completed in September 2022. The resulting 5G NR NTN solution eventually re-use as much as possible protocols, procedures and architecture already defined for terrestrial 5G NR to minimize the impacts at User Equipment (UE), Radio Access Network (RAN), 5G Core (5GC) level. Thus, NTN has been integrated as a part of the 5G NR technology by adapting some part of the RAN protocols and architecture specific to the satellite access. In Rel-17, the NR based satellite access aims at serving handheld devices through a transparent satellite that relay the 5G signals between the UE and an on-ground base station (gNB).

5G-Advanced marks another major evolution in 5G technology. Started at Rel-18, currently at the end of the normative phase, this new evolution set to evolve 5G to its full potential by strengthening the network performance and by providing connectivity to all devices. The NR NTN enhancements is defined on this way to support new scenarios covering deployments in frequency bands above 10GHz and several enhancements for the mobility and the coverage. The upcoming Rel-19 should bring a new step for a better integration of the 5G with the regenerative payload architecture where the gNB is on-boarded inside the satellite, enabling a more efficient and more flexible non-terrestrial network. The regenerative payload architecture also provide a better complementarity between TN and NTN by enabling a better service continuity and new space-based services. Such enhancements will prepare the way towards the next generation of mobile communications, 6G. 3GPP NR NTN system so far is described in the section entitled “NTN Integration in 5G Ecosystem”.

In 2021, ITU-R WP 5D initiated the development of the vision for IMT-2030 and beyond. In this vision, nine 5G capabilities are enhanced, i.e. peak data rate, user experienced data rate, spectrum efficiency, area traffic capacity, connection density, mobility speed, minimal latency, data reliability and security (including privacy and resilience). Six new capabilities appear with 1/ coverage, 2/ network sensing, 3/ Artificial Intelligence (AI) and

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[1] TR 21.915, “Summary of Rel-15 Work items”.

[2] TR 21.916, “Summary of Rel-16 Work items”.

[3] TR 21.917, “Summary of Rel-17 Work items”.

Machine Learning (ML), 4/ sustainability, 5/ fine-grain positioning and 6/ interoperability. The ITU-T Focus Group technologies for network 2030 (FG-NET-2030) defined in 2020 a set of preliminary target services for 6G. In this vision, 6G systems are expected to create a fully connected world, with the convergence of the physical, human, and digital domains. 5G-PPP defined three new classes of interactions that will be possible with 6G, 1) Digital twinning of systems e.g. digital twin of a factory; 2) Connected intelligence where the network serves as a key infrastructure with trusted AI functions; 3) Immersive communications where high-resolution visual/spatial, tactile/haptic and other sensor data can be carried at an extremely high throughput and low latency. It is agreed that the full integration between terrestrial and non-terrestrial network will essential in 6G. Among enhanced and new capabilities from the IMT-2030 vision, NTNs are necessary at least for coverage, interoperability, sustainability and security capabilities. In this vision, NTN is not only a complement of the terrestrial network but also a solution, pushing towards a unified communication system as illustrated in the Figure 1.

The 3GPP effort of standardization for 6G should begin at the Rel-19 with 6G requirements and continues in Rel-20 for studies and Rel-21, by 2027, for the 6G specification. In the 6G systems, TN and NTN will be unified and fully integrated into a multi-dimensional, multi-layered, multi-band infrastructure to provide a comprehensive connectivity solution aligned with the IMT-2030 vision. The architecture is presented in the section entitled "6G as a Multi-Dimensional System for a Comprehensive Connectivity Solution".

Finally in the section entitled "Technologies enabling 6G NTN", we review a number of promising technologies for 6G including waveforms, AI/ML models and satellites architecture.

## NTN INTEGRATION IN 5G ECOSYSTEM

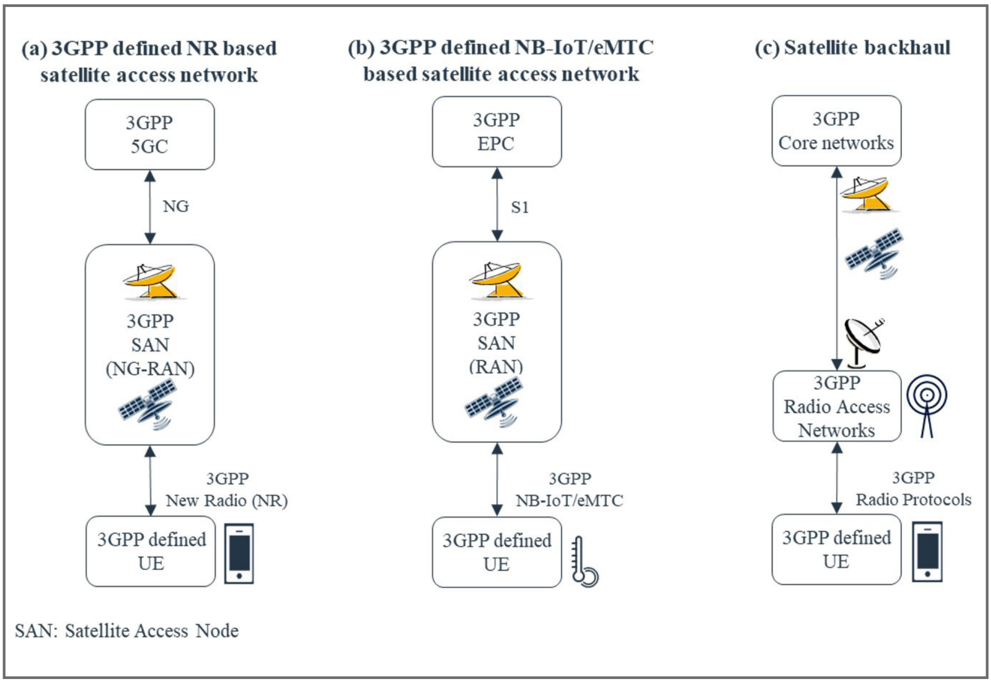

Figure 2: 3GPP Satellite network solutions.

The following satellite network solutions have been integrated within 5G System (5GS) starting from 3GPP Rel-17 as illustrated on the Figure 2 above, with the following components:

(a) 3GPP defined NR based satellite access network: NG-RAN based on satellite access nodes, connected to a 5GC, providing eMBB-s (enhanced Mobile Broadband for satellite) and HRC-s (High Reliability Communications for satellite) services to 3GPP defined UE. It supports the 3GPP defined NR access technology and may also provide connectivity to IAB nodes. It belongs to the 3GPP defined “NR_NTN_solutions”.

(b) 3GPP defined LTE based satellite access network: E-UTRA Radio Access network based on satellite access nodes, connected to an EPC, and provides mMTC-s services to 3GPP defined user equipment. It supports the 3GPP defined NB-IoT or eMTC access technology. It belongs to the 3GPP defined “IoT_NTN_solutions”.

(c) Satellite backhaul: A transport network over satellite that provides connectivity between 5GC and gNB. This transport network may be based on 3GPP or non 3GPP defined radio protocols.

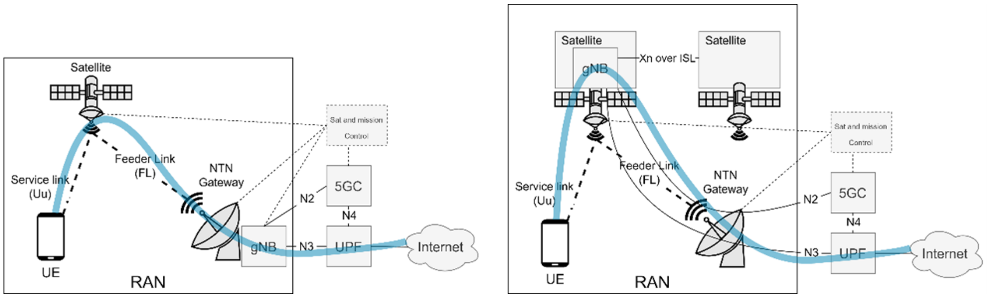

Figure 3: 5G NTN RAN architectures.

In this paper, we focus on 3GPP work related to satellite-based NR NTN since Rel-15. We will not detail airborne-based architecture (e.g. HAPS, HIBS, UAV) and we will not consider specificities related to the Internet-of-Things (IoT) NTN.

The Recommendation ITU-R M.2083 on the IMT-2020 vision, identifies three usage scenarios for IMT-2020 and beyond: Enhanced Mobile Broadband (eMBB), Massive machine type communications (mMTC) and Ultra-reliable and low latency communications (uRLLC). Satellite networks are considered to provide variants of eMBB, mMTC and uRLLC: eMBB-s, mMTC-s and HRC-s usages scenarios. NTN in 5G offers a complementing role to TN access. Combine the NTN & TN for service continuity and reinforced reliability and availability. Due to their wide coverage, resiliency, multicast and broadcast capabilities, satellite systems provide scalable and efficient network solutions. Therefore, both geostationary and non-geostationary mobile satellite systems have a role to play in this context.

A list of technical performance requirements for the satellite component of IMT-2020 have been elaborated and defined for the satellite radio interface, including for instance a user experienced data rate of 1Mbit/s in the DownLink (DL) and 100kbit/s in the UpLink (UL). An important part of the 3GPP work was thus related to the self-evaluation of ITU-R defined requirements for 5G satellite (NTN) radio interface while re-using the existing terrestrial 5GS. The main challenges were related to: 1) a technical challenge related to the specific characteristics of a wide range of satellite network deployment scenarios compared to existing terrestrial mobile network; 2) an architectural challenge related to the specific network architecture and movement of the satellite constellation; 3) a spectrum challenge for NTN satellite frequency bands related to co-existence studies, RF and RRM requirements.

## The technical challenge

The integration of 5G satellite-based components in the 5GS is a technical challenge, particularly due to specific characteristics of the satellite radio interface and the wide range of satellite network deployment scenarios compared to the Earth cellular networks. Especially, the long propagation delays, large Doppler effects and moving cells characteristics did not exist in terrestrial, or at a small scale.

The propagation delays is inherent to the altitude and the position of the satellite regarding to the UE and the gateway. The round-time latency of an order of one millisecond in terrestrial is above 10ms for a LEO satellite and 500ms for a GEO. Timers related to the different procedures has been adapted for the NTN in Rel-17. The latency poses also a question for the synchronization of the command and offset has been introduced. Inside a cell of an hundred kilometers wide, the differential delay between a UE at the nadir and at the edge is quiet important and need a synchronization at the base station. Synchronization also between the uplink and downlink frames that need to arrive at the correct sub-frame at the gNB.

The satellite motions (i.e. in LEO) have an impact of the delay variation up to +/4 µs/sec. The motion causes a Doppler shift as well as a Doppler variation proportional to the cell size and the speed of the satellite as seen by the UE. The time and frequency synchronization of the UE is very dependent to the Doppler and Timing estimation of the service and the feeder links. To perform this estimation and derive the satellite movement, the UE relies on the broadcasted ephemeris data by the network via the SIB19 NTN-specific system information (or equivalent SIB31/SIB32 NTN-specific system information for IoT-type of devices).

The consequence of the satellite movement that required an important work at the 3GPP was for instance the dynamic cell pattern on the ground. Steerable beams are generated by the satellite to provide quasi-Earth fixed beam foot print on the ground or satellite-fixed beams are generated by the satellite and hence the beam footprint on the ground with the satellite motion. In one case or the other, it implies a great mobility due to satellite in addition to the UE mobility that exists in the terrestrial. The 3GPP introduced in Rel-17 and more in Rel-18 mechanisms to make the transition from one beam to another (inter-beam mobility), to one cell to another (inter-cell mobility), to one satellite to another (inter-satellite mobility) or to one gNB to another (inter-gNB mobility) as continuous as possible to avoid disruption and quality of service degradation. The inter-gNB handover (HO) procedure is re-used as a baseline but NTN introduced also time-based and location-based Conditional Handover (CHO) where the network indicates to the UE to move to a candidate cell (of another satellite or another gNB) when a time or location based event is fulfilled. Time-based or location-based CHO is particularly adapted to the satellite system where the trajectories and transition time are highly predictable. The frequent change of the satellite and the serving cell justified also to reduce the signaling and the interruption time for the UE. For that, the satellite switch with re-rync[4] offers a procedure that avoid L3 mobility (i.e. handover). Finally, in the legacy handover procedure, the UE re-synchronize with the new gNB with a Random Access (RACH) procedure that introduces an interruption time and a congestion at the gNB when lot of UE move from one cell to another at the same time. RACH-less procedure solves this issue by allowing the UE to synchronize to the target cell without performing a RACH. It is possible thanks

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[4] Called unchanged PCI during the Rel-18 normative phase.

to the satellite ephemerides and NTN information provided by the SIB19, allowing UE to detect the target satellite and synchronize in time and frequency to it. However, the mobility management implementation remains a challenge in the current 5G NTN and some path remains open in Rel-19 and Rel-20 to ensure a service continuity to the UE.

## The satellite RAN architecture challenge

Rel-17 and Rel-18 satellite RAN uses a satellite transparent payload architecture where the payload relays the 5G signals between UE and gNB and maps beams. The regenerative payload architecture will be introduced in Rel-19 and Rel-20 where the gNB is fully or partially on-boarded on the satellite, enabling space-based connectivity potentials. Coupled with the inter-satellite links (ISL) and mega-constellations technologies, 5G NTN will unleash throughputs and flexibility. A necessary step towards the 6G unified global connectivity service.

From Rel-17, the satellite based RAN is by default connected to a 5GC. A satellite RAN can be shared between more than one core networks. Therefore, the same UE can be connected to a satellite or a terrestrial access network transparently thanks to the 5G NTN architecture solutions based on common access technologies and interoperable networks.

## The NTN frequency bands and related requirements challenge

For the first time, 3GPP considered in Rel-17 the introduction of Mobile Satellite Service (MSS) frequency bands for 3GPP User Equipment (UE) direct connectivity with satellites and had to consider the coexistence in adjacent bands with Terrestrial Networks (TNs). 5G NR NTN (Non-TN) used for satellite communications is therefore representing a major breakthrough in the history of telecommunication for the capability of reuniting two different types of services, i.e. terrestrial and non-terrestrial, by reusing the same waveform and potentially the same type of terminal, opening new market opportunities for both terrestrial and non-terrestrial stakeholders.

A challenge related to the NTN spectrum lies on the waveform to be used for satellite access and the related NTN-TN co-existence studies in adjacent bands, starting with the introduction of n256 and n255 S- and L-bands operating in FDD duplexing mode. Rel-18 introduced the satellite Ka-band (above 10GHz frequency spectrum) with n512, n511 and n510, and Rel-19 will follow with discussion for introduction of Ku satellite band for 5G NR NTN.

The frequency bands currently defined as part of Rel-17 and Rel-18 3GPP work (where FR1-NTN refers to 410 MHz – 7,125 MHz frequency range, and FR2-NTN currently refers to 17,300 MHz – 30,000 MHz frequency range) are described in the tables below:

Table 1: NTN operating bands in FR1 for satellite networks (FR1-NTN).

| NTN satellite operating band | UpLink (UL) operating band SAN receive / UE transmit FUL,low – FUL,high | DownLink (DL) operating band SAN transmit / UE receive FDL,low – FDL,high | Duplex mode |
|---|---|---|---|
| n256 | 1,980 MHz – 2,010 MHz | 2,170 MHz – 2,200 MHz | FDD |
| n255 | 1,626.5 MHz – 1,660.5 MHz | 1,525 MHz – 1,559 MHz | FDD |
| NOTE: NTN satellite bands are numbered in descending order from n256. | | | |

Table 2: NTN operating bands in above 10 GHz for satellite networks (FR2-NTN)

| NTN satellite operating band | UpLink (UL) operating band SAN receive / UE transmit FUL,low – FUL,high | DownLink (DL) operating band SAN transmit / UE receive FDL,low – FDL,high | Duplex mode |
|---|---|---|---|
| n5121 | 27.5 – 30.0 GHz | 17.3 – 20.2 GHz | FDD |
| n5112 | 28.35 – 30.0 GHz | 17.3 – 20.2 GHz | FDD |
| n5103 | 27.5 – 28.35 GHz | 17.3 – 20.2 GHz | FDD |
| NOTE 1: This band is applicable in the countries subject to CEPT ECC Decision(05)01 and ECC Decision (13)01.<br>NOTE 2: This band is applicable in the USA subject to FCC 47 CFR part 25.<br>NOTE 3: This band is applicable for Earth Station operations in the USA subject to FCC 47 CFR part 25. FCC rules currently do not include ESIM operations in this band (47 CFR 25.202). | | | |

Table 3: Other NTN band introductions (through Release-independent Work Items).

| NTN satellite operating band | UpLink (UL) operating band SAN receive / UE transmit FUL,low – FUL,high | DownLink (DL) operating band SAN transmit / UE receive FDL,low – FDL,high | Duplex mode |
|---|---|---|---|
| n254 | 1,610 – 1,626.5 MHz | 2,483.5 – 2,500 MHz | FDD |
| NOTE: NTN satellite bands are numbered in descending order from n256. | | | |

Moreover, study and normalization phase simulation work showed that satellite connectivity does not require a dedicated satellite waveform since 5G New Radio technology based on CP-OFDM (for Downlink) and DFT-s-OFDM (for uplink) can be sufficient for satellite communications. The TN-NTN co-existence issue was also extensively studied in Rel-17 and Rel-18 and concluded that TN can co-exist with NTN on adjacent channels with relaxed Adjacent Channel Interference Ratio (ACIR).

As a matter of fact, one of the major conclusion of the 5G NTN 3GPP work in Rel-17 for FR1-NTN was that NTN UE could reuse the current Radio Resource Management (RRM) and Radio Frequency (RF) requirements of the TN UE. For this reason, at least in FR1-NTN, the same terminal (and not only dedicated satellite terminal) can connect to both TN and NTN.

## 6G as a Multi-Dimensional System for a Comprehensive Connectivity Solution

In an order to meet the IMT-2030 vision and performance requirements and to foster the connection among the physical, digital and human domains, a new comprehensive system should be defined for 6G such as the multi-dimensional, multi-band, multi-layer architecture presented in Figure 4.

In addition to the terrestrial networks that provide a horizontal connectivity, the system is augmented by a vertical connectivity constituting a third dimension. 5G already support the non-terrestrial segment but the novelty of the 6G system is the native integration of this segment in the same unified 6G network for increased resiliency. For that, the space

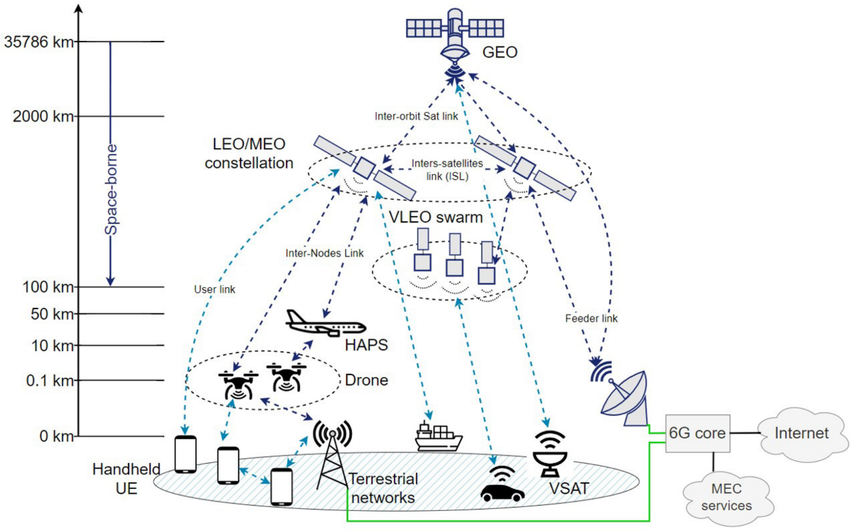

Figure 4: Multi-dimensional architecture.

segment will not be only a relay of the terrestrial signal but an active component of the network. The space segment not only composed of LEO/GEO satellites is constituted of nodes. They constitute a multi-layer architecture where nodes can communicate with each other by means of Inter-Node Links (INL), e.g. Inter-Satellite Links (ISL) intra-/inter-orbits and with the ground through service and feeder links. Such links use different technologies, radio at different frequencies, laser, optical constituting a multi-band infrastructure. Each nodes provides a service adapted to its capacities and orbits. For instance, 1) GEO satellites provide continental fixed coverage ground interesting for multicast/broadcast services, has a large view field on lower layers, large computational capacities and important transmission power; while 2) LEO satellites constellation offer lower latency along with better coverage but with a reduced payload capacities. GEO, LEO, UAV, HAPS are therefore complementary to provide connectivity to heterogeneous services and constitutes the different layers of the system.

Finally, the proposed architecture and the 6G technology perspectives implies an important thought on the evolution of the packet mobile core, the RAN-core convergence, the support of non-3GPP access, and the decentralization of the network functions. Based on the proposed architecture and the above observations, below we thoroughly review the most relevant technologies for 6G communications.

## TECHNOLOGIES ENABLING 6G NTN

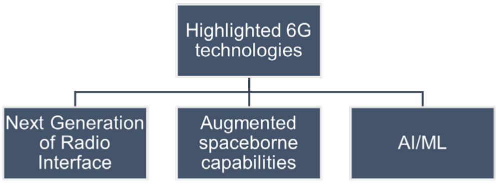

Figure 5: Highlighted 6G technologies.

In this part, we highlight some probable 6G building block technologies for the multi-dimensional architecture. Summarized in Figure 5, it implies new generation of radio interface technologies, augmented spaceborne capabilities and Artificial Intelligence for network. It shall to be noticed that some of these technologies are already discussed for 5G advanced, therefore, there is not an abrupt separation between 5G Advanced and 6G.

For the next generation of Radio interface, alternatives waveforms are discussed to improve PAPR, spectral efficiency, RRM, out-of-band emission and co-existence. Non-Orthogonal Multiple Access (NOMA) and different variants of OFDM are considered. Co-ordinated Multipoint (CoMP) transmissions enable seamless, efficient transmission. NTN asynchronous Multi-connectivity (MC) and Carrier-Aggregation (CA) improves the throughput and the spatial diversity for hardened radio interface. Bandwidth part (BWP) for NTN is promising for a flexible bandwidth optimization and management. In-Band Full Duplex (IBFD) is an interesting evolution of the FDD-only duplexing scheme for NTN. Together, these enhancements will allow a new set of NTN-compatible devices such as Reduced Capabilities devices (RedCap UEs). Reflecting Intelligent Surfaces (RIS) will be able to provide indoor connectivity to NTN, which is not possible today. Sensing-based cognitive radio will allow a dynamic reconfiguration of the radio interface to the user service and the radio channel environment for a better efficiency of the RRM. Software-defined Network (SDN) are necessary to allow robust, seamless inter-layer mobility and reconfiguration. Finally, trust and the security of the radio interface will benefit from homomorphic encryption and block chain technologies.

The spaceborne-related technology evolved quickly since a decade thanks to new actors taking part to the New Space revolution. These technologies, hardware and software developed are essential enablers for the 6G. Next generation of regenerative payload includes new design of active antenna (e.g. reconfigurable phased antennas, meta-surface antennas…) for advanced beam management, advanced On-board Processing, software-defined payload, on-board network functions. Satellite constellations will be more heterogeneous with multi-orbit architectures, different satellite size (e.g. nano/pico satellites) and more reconfigurable enabled by Inter-Satellite Links (e.g. using optical wireless communication) and network and service orchestration and management (e.g. SDN for space). Relay-based architecture could be considered in the constellation using Integrated Access and Backhaul (IAB) for resilient networks. Thanks to the augmented payload capacities, the constellation will offer a new set of services such as space-based edge computing for low latency services or Positioning Navigation Time (PNT) services in complement to GNSS and therefore allowing GNSS-independent UE connectivity (e.g. for RedCap UE).

Finally, AI and ML techniques are widely recognized as a necessary solution for 6G dynamic and information-rich contexts 6G communications. Among these, RRM algorithms including beamforming and beam hoping are one of the most promising application. AI-based channel estimation and scheduling are very promising since NTN systems are not obvious, since the UE performance can only be known after the beamforming matrix has been computed. The legacy algorithms have difficulties to optimize in real-time the radio interface. Some references propose also to use AI for channel modeling, handover and interference management.

## Conclusion

For a long time, the terrestrial and satellite network technologies where considered as addressing disjoint markets. Non-Terrestrial access solutions have been added in the 5G system as a complementary access for service continuity. NTN solutions standardized since Rel-17 solve important key issues to mitigate the satellite network specifics (e.g. Doppler, latency, etc.) in order for 5G system to support satellites. 6G as envisioned by the ITU-R IMT-2030 will be a further step towards the unification of the communication technologies to provide new sustainable, resilient and trustable network capabilities able to support the interactions between the human and its physical environment leveraging real time digital modelling. The proposed architecture based on multi-dimensional, multi-layer, multi-band is a solution to meet 6G vision of a comprehensive communication system and unleash new network potentials. The possible enabling technologies for such architecture has been discussed. These technologies should be subject of a possible standardization roadmap in the context of 3GPP.

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