NetWorld Europe

Enabling Technologies for Future Vertical Ecosystem Transformation Working Group

White Paper Series

White Paper #1: Technologies & Standards to Enable Vertical Ecosystem Transformation in 6G

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EXECUTIVE SUMMARY

This whitepaper is the first of a series of whitepapers focusing on the enabling technologies in the 6G era and their transformative impact on the society, the economy, and the environment, with a strong focus on current and emerging vertical sectors.

The paper begins by discussing the emerging 6G era, its impact on the digital economy, and the need for vertical ecosystem transformation to realize the full potential of this new technology. It then outlines the key standards and enabling technologies that are driving the transformation of vertical ecosystems, such as network slicing, virtualization, artificial intelligence, and edge computing. Finally, the summary highlights the challenges and opportunities associated with this transformation, as well as the potential impact of 6G on the digital economy. The paper focuses on the new user equipment, advanced radio technology, advanced network technology trends, integrated terrestrial and non-terrestrial networks, artificial intelligence and machine learning, integrated sensing and communication, advanced ICT, digital twin and trust and security.

This whitepaper is an essential initial read for organizations looking to capitalize on the disruptive potential of 6G technology. The findings of this paper will provide valuable insights for industry stakeholders, policy makers and researchers, and in particular those looking to unlock the potential of 6G in transforming the future vertical ecosystem.

1 INTRODUCTION

1.1 BACKGROUND

An important mandate of NetworldEurope, as key stakeholder in the European Commission's (EC) Smart Networks and Services (SNS) Joint Undertaking, is to engage with a wide range of vertical sectors and stakeholders which are future beneficiaries of SNS. To this end, a new Working Group (WG) on 'Enabling Technologies for Future Vertical Ecosystem Transformation' was established. The WG complements and extend the Vertical Task Force activities with the 6G Smart Networks and Services Industry Association (6G-IA), focusing on advancement in the following key directions:

- Roadmaps, future/long-term requirements, technology, and research aspects rather than prototypes and products,
- global outreach for extended the discussion and engagement, and
- technology enablers and disruptive business transformation aspects.

Consequently, the WG on Enabling Technologies for Future Vertical Ecosystem Transformation has agreed on the following scopes with respect to the technology, economic and societal aspects:

- Technology aspects
    - Exchange/sharing of long-term roadmaps from the vertical domains versus communication domain with the view to beyond-5G and 6G evolution.
    - Elicitation/exchange of user/function requirements.
    - Compatibility/integration and transformation of architectures.
    - Blueprints for common reference points and interfaces.
- Economic and societal aspects
    - Contributions for consideration of restructuring business models in the telco and vertical ecosystem.
    - Future challenges and markets in the vertical sectors and relationships with communication domain stakeholders.
    - Sustainability, environmental impacts and Netzero.

This is the first White Paper outputs from the WG, which, in line with the scope of the WG, provides a holistic view on emerging and future communication and networking technologies that are expected to play a key role in accelerating future digital transformation of the vertical ecosystem. In the first White Paper we take a 'deep dive' into the standards and enabling technologies which advance the verticals in the transformation from 5G to 6G. Vision for Enabling 6G Vertical Ecosystem Transformation.

5G in conjunction with Internet of Things (IoT), Artificial Intelligence (AI), and cloud technologies will drive a significant digital transformation to fulfil the vision for the fully connected, digitalized carbon-neutral society and industries [1.1-2]. Unlike the previous generations, 5G is offering not only ultrafast (20 Gbps peak data-rates) but also ultra-reliable, ultra-low-latency (1 ms) and massive connectivity capabilities as shown in Figure 1.2-1. In comparison with previous generation, 5G also comes with significant architectural innovations including network slicing, private networks, and edge computing. Armed with the above features, 5G is proving successful as the first generation of mobile communication systems to achieve the long-anticipated expansion of operator's connectivity services into vertical sectors, enabling new types of usage, and new Business-to-Business (B2B) user communities. Prominent success story examples of 5G for verticals include manufacturing and automotive sectors. When we begin to focus on the next step that is beyond 5G (B5G)/6G, it is essential to consider the enabling technologies for transformation of vertical sectors which are discussed in Section 4. Besides technology push transformation of these sectors is prominently and increasingly impacted by the economic, business, and societal requirements which will be discussed in a future white paper. When we compare the earlier visions of mobile communication to networks and current vision for 6G, we can see some differences. The era for digital mobile data started with 3rd Generation, which created the foundations for mobile broadband communications and enabled for example multimedia content delivery through cellular networks. In 4G, the main focus was to enable better broadband connectivity for mobile end users and provide a variety of Internet services such as video content and social media services for end users. With the evolution of cellular system standard, also the capabilities to industrial use have been introduced within 4G Long Term Evolution. For example, the cellular Internet of Things (cIoT) solutions enable the transition from non-cellular IoT network to support, e.g., mobility, long battery lifetime and larger coverage areas. While 4G was mainly to boost the cellular network capacity for single use/user and provide improved broadband connectivity for end-users, 5G has been more to enable efficient connectivity solution for various industrial verticals with the same system architecture.5G system is also enabling larger bandwidths, lower latencies, improved security enablers and reliable communications through the new system architecture solutions and support for various new frequency bands from sub-6GHz area to millimetre wave frequencies.

The vision of 6G is strongly driven by the United Nations (UN) sustainable development goals (SDG) in a global perspective. These goals are stating the high-level requirements of environmental sustainability, not only for the technology development, but also in human-centric and societal context. In the European context, the policy objectives related to ensure the European industry's competitive edge and sovereignty, digitalization and industrial transformation towards sustainable development will also require development of new communication technologies. The communication technology will be a tool to enable the sustainability goals for various vertical segments, but at the same time the same sustainability goals needs to be taken into consideration in communication technology.

What is then the vision towards 6G and what is its relation to verticals?

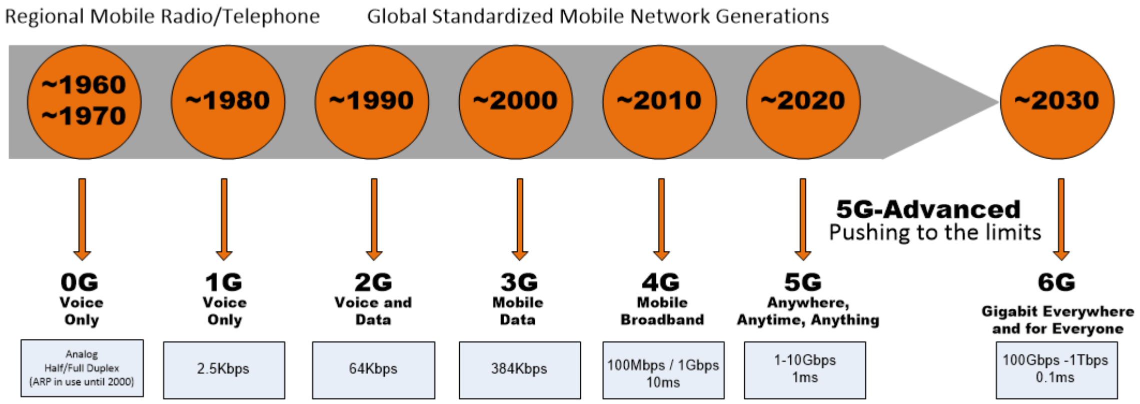

Figure 2.2-1 Over 40 years of mobile communication standards evolution from 1G to 5G and the expected timelines to 6G.

6G should enable the evolution of current vertical use cases in 5G, as well as should allow new use cases within existing verticals, and also new verticals with new use cases. It also should support vertical sectors in addressing global grand challenges such as climate change, aging population, mobility, environmental management, resource sufficiency, and digitalization of industry and citizen services. Furthermore, starting with 5G, the communication networks are the key enablers for bringing together artificial intelligence, big data, and high-performance computing. 6G trusted and secure connectivity by design will continue to have a central role in enabling cybersecurity for critical services and infrastructures of society and with focus on industrial use cases security requirements.

The evolution of vertical solutions in 5G towards 6G should target a shift from on premise to 'as a service' solutions, possibly integrated with software ecosystems: not only telecom services in other words, but a complex ecosystem of data, software and integration/support services. But, what does it mean for the EU industry? It may be necessary to go beyond the idea of network services, the 'network slices', towards a wider concept of telco digital ecosystem, conveying a more open innovation to the verticals. In this sense initiatives such a GAIA-X/IDS [1.3] are potential amplifiers of such an evolution.

Finally, the impact of mobile technologies on economic growth have been raising with each new generation after 2G and this trend will continue and, we expect, further accelerate in 6G as shown in Figure1.3-2. In Europe, the income per capita rose by $550, due to the expansion of mobile technology, which is 8% of income per capita growth throughout the last 20 years. In the next 10 years, 5G could enable 2.1% of global income growth playing an important role in economic recovery and future productivity growth. According to an EU study [1.4] 5G investments in *Europe* estimated for 2020 will reach 56 billion€ and will have a trickledown effect (calculated with an input output analysis) across the whole EU economy estimated at 141billion€ creating 2, 4 million additional jobs. Benefits are of first order (direct impact) for services & goods producers and of second order (indirect impact arising from knock on impacts of goods and services impacted by 5G.

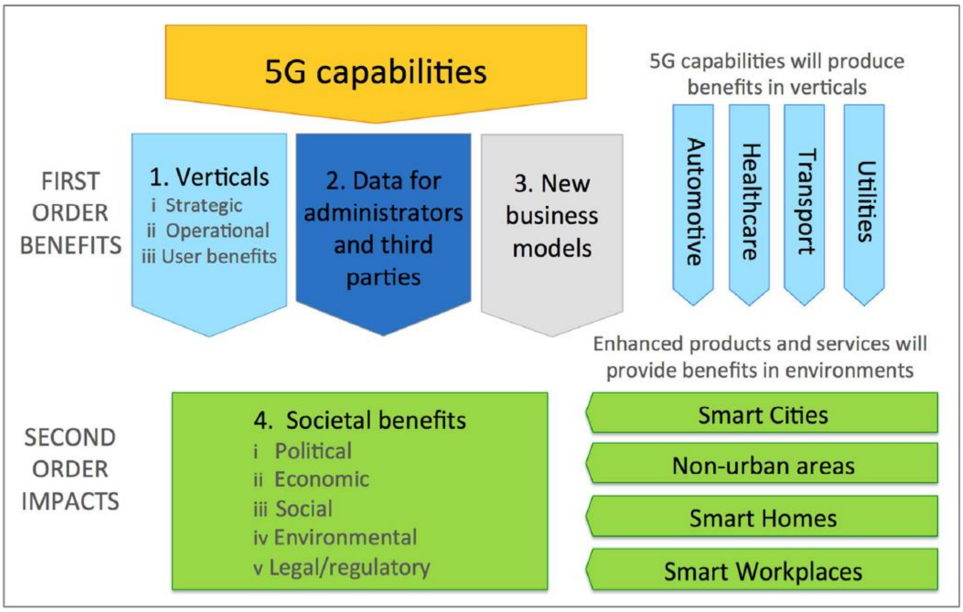

Figure 1.4-2 5G capabilities and their socio-economic befits and impacts.

The most impacted sectors are Automotive, Healthcare, Transport and Utilities for which a global benefit of 113billion€ has been estimated – 62.5billion€ are the direct benefits while 50.5billion€ are the indirect benefits calculated for 4 environments (smart cities, non-urban, smart homes and smart workplaces). According to a more recent study published by Accenture [1.5], 5G will add 1 trillion€ to the EU GDP of direct effect between 2021 and 2025 adding/transforming up to 20 million jobs across all sectors. This includes direct, indirect and induced effects of investments in 5G. To extrapolate to the impact of 6G on the European Economy starting from 2030, we will consider in a future White Paper the GSMA econometric model developed over 20 years (2001-2020) encompassing worldwide data [1.6]. This model estimates that a 10% increase of mobile adoption brings to an increase of 0.5% to 1.2% increase in GDP being the lower end of impact typical of developed economies such as Europe. Each new generation of mobile technologies adds 15% of economic impact in a green field scenario, while in case of technology substitution (brownfield scenario) the economic impact evaluates the 15% of the Greenfield adoption scenario. The sum of the human and IoT factor will provide the global economic effect of 6G on European economy starting from 2030.

1.2 STRUCTURE

The White Paper is organized as follows. Chapter 2 surveys the state-of-play in 5G standards with a focus on Verticals. Chapter 3 describes on the architecture, networking, and radio technology advancement towards 6G focusing on current and future vertical requirements. Chapter 4 examines a number of key enabling technologies, such as AI and ISAC, that are expected to play a major role in future transformation of verticals. Section 5 concluded the White Paper and highlights global communication grand challenges.

2 VERTICALS IN 5G

This section reviews the 5G and B5G standardization activities mainly within 3GPP. It will then tie those activities to regional 5G vertical development to gain an understanding of how current vertical requirements are being addressed in 5G and B5G standards.

2.1 CURRENT STATUS OF STANDARDS

As 5G systems evolve through the years, more and more standardization bodies are involved in the definition of what B5G will look like, e.g., the 3rd Generation Partnership Project (3GPP), European Telecommunications Standards Institute (ETSI), IEEE, and IETF just to name a few with the most active standard bodies in defining current and future 5G releases to be the 3GPP.What follows is a short overview of the path done so far and what the next steps are towards 5G-Advanced systems are summarized, focusing on the 5G verticals related aspects.

2.2 RELEASE 15 (5G PHASE 1)

The standardization of what the market and the communication ecosystem nowadays call ‘5G systems’ started in 3GPP standardization back in 2015. The first 3GPP technical specifications made available in late 2017 describing a working 5G system, called the 3GPP Release 15 (Rel-15) (aka ‘5G Phase 1’) and finalized in 2019 [2.1]. While a number of technical specifications created by 3GPP SA, RAN, and CT groups was in progress, the first commercial 5G system was deployed with partially-3GPP-compliant in 2018 and fully-3GPP-compliant in 2019.

The main focus of 3GPP Rel-15 was on building the basic blocks of 5G systems and on supporting enhanced Mobile Broad Band (eMBB) services [2.2]. The 5G verticals that first benefitted from 5G Phase 1 are those that utilize eMBB capability and therefore high bandwidth applications, for instance Media & Entertainment (for Augmented and Virtual reality), Automotive (for vehicle-to-vehicle communications), and the Industrial Internet of Things (IIoT) domain in large industrial areas such as surveillance monitoring applications.

2.3 RELEASE 16 (5G PHASE 2)

3GPP Rel-16 enhancements (completed in June and July 2020), add new features and functionalities evolving the 5G system defined in 5G Phase 1 to what is known as ‘5G Phase 2’.

3GPP Rel-16 entails two main set of improvements and features that can meet the vertical requirements:

Efficiency Items: a set of improvements and enhancements on different key functionalities, which evolve and improve the core 5G system functionalities as defined by the 5G Phase 1, e.g.:

- Positioning precision,
- MIMO,
- Power consumption efficiency,
- Dual connectivity capability,
- Self-Organizing Networks and Big Data support, and
- Interference mitigation.

Expansion items: a set of new features focused on adding to 5G systems functions to more smoothly interact and serve 5G verticals, and supporting of unlicensed bands, e.g.:

- 5G Vehicle_to_Eeverything (V2X),
- 5G Industrial IoT,
- 5G Ultra-Reliable and Low-Latency (URLLC) enhancements, and

- 5G for unlicensed spectrum operation.

The 5G verticals benefitting mainly from Phase 2 features are those leaning on URLLC services, like Automotive (via the introduction of the V2X related work item) and IIoT (thanks to the capability of managing unlicensed spectrum chunks in big industrial areas like factories and ports).

2.4 Release 17

Stage 1 and Stage 2 completion dates followed the schedule agreed-upon at the end of 2019 despite the pandemic outbreak, at the cost of making Rel-17 a bit leaner, i.e., by shifting a few Work Items into Rel-18 and shown in the following figure.

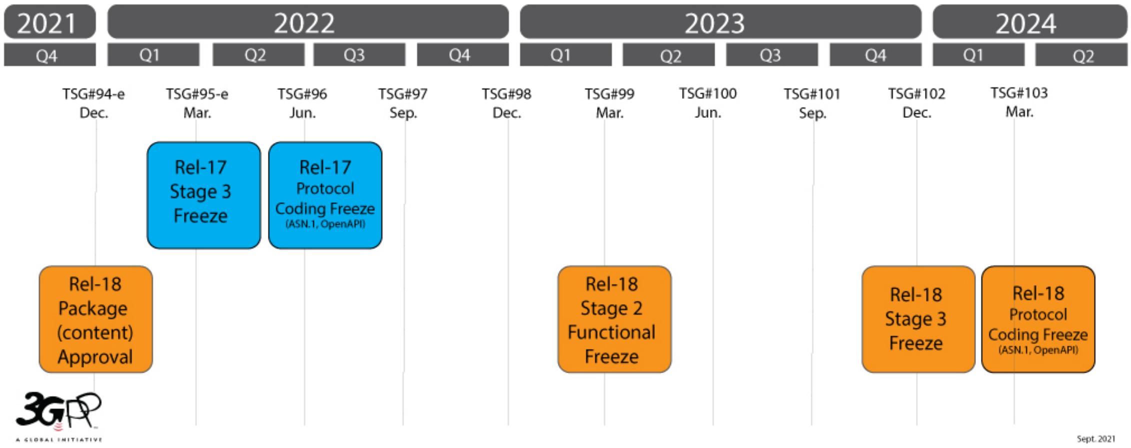

Figure 2.4-1 3GPP Rel-17 and Rel-18 Roadmaps[1]

For more details on the planned completion date of the different 3GPP groups are described in 3GPP document SP-211141.

Among almost 40 3GPP Rel-17 features enhancing existing functional blocks of the 5G architecture, followings are relevant to 5G Verticals:

- MIMO enhancements like the multiple transmission and reception point (mTRP)
  - Especially benefitting 5G Verticals based on eMBB and URLLC services.
- Small-data transmission:
  - This is one of the features that facilitates the massive Machine Type Communication (mMTC) services, valuable for all IoT related 5G verticals, such as Smart cities and IIoT.
- Reduced-Capacity UE:
  - Key for IIoT (smart sensors) and wearables with reduce computational capabilities and power resources.
- Addition of new bands (52.6 GHz to 71 GHz):
  - eMBB-based 5G Verticals will benefit from the huge increase in bandwidth that such new bands can provide.

[1] Source 3GPP Website https://www.3gpp.org/news-events/2228-rel-17_f2f.

- Non-Terrestrial-Networks:
    - Improving, and even in some cases allowing for the first time, coverage in remote areas allows for a pervasive use of sensors and machine-type communication-based 5G Verticals.
- Non-Public Networks (Private Networks):
    - IIoT will be the main beneficiary of such enhancements.
- Positioning:
    - IIoT and Automotive to reach ~30 cm position accuracy, as well as benefitting remote control applications.
- Extended Reality:
    - All 5G Verticals based on eMBB services will make use of a low-latency and high bandwidth capability that this feature will allow.
- Enhanced V2X Services:
    - Automotive is the target 5G Vertical for this feature.

2.5 Release 18

3GPP has introduced the term '5G-Advanced' for the features and enhancements starting with 3GPP Rel-18 and paving the way to the first 6G releases, expected not before Rel-21, around 2027/2028.

Regarding the content of Rel-18, in addition to enhancements to existing features like network slicing and IMS evolution, the most relevant features to this whitepaper are mainly divided in the following two blocks:

New Features, like

- AI/ML support for new and optimized 5G services,
- Vehicle-mounted relays,
- Tactile services,
- Data integrity,
- Timing resilient services,
- Personal IoT and residential networks.

5G-Vertical focused features, like

- Smart energy infrastructure,
- Low-power high accuracy positioning for IIoT scenarios,
- Service exposure interfaces for IIoT scenarios,
- Mission critical services enhancements,
- Satellite access to support control and video surveillance.

To this end, Rel-18 is expected to bring more intelligent and self-managed services, with increased location capability, security, and reliability.

2.6 Release 19

The timeline and the content of 3GPP Rel-19 was started to be discussed in Q4 2021 and aims to kick start mid 2023.

Regarding the content, even though some Study Items have been proposed, e.g., on advanced spectrum sharing schemes, interactions between robots and humans, and advanced drone capabilities, no consensus has yet finalized.

2.7 5G VERTICAL DEVELOPMENTS BY REGION

2.7.1 Europe

Europe has been at the forefront of 5G launches. In mid-2020, 5G commercial services were available in 15 European countries. While 5G appeared on the mass market with consumer facing offers, 5G was validated (i.e., design was checked for its appropriateness to meet verticals' requirements) and evaluated (i.e., quantitative information of some characteristics of a certain design, such as key performance indicators, were computed) for industrial applications in more than 180 trials across 28-member states. In the automotive sector trials are taking place at a pan-European scale through 11 cross-border corridors. Vertical trials have been performed through 5G Public Private Partnership (5G PPP) projects funded by 700M€ of the European Union research funding grants and matched by 700€ of private funding in the 2014 – 2020 timeframe. The 5G PPP has already covered a range of vertical industries. Examples are listed in Table 1 [2.3].

Table 2.2.1-1 Vertical sectors covered by the EU Horizon 2020 5G PPP projects [2.3].

Vertical sector	5G PPP Project
Automotive/Transport	5GENESIS, 5G VINNI, 5G HEART, 5G!DRONES, 5GROWTH, 5G TOURS, 5G VICTORI
Manufacturing	5G EVE, 5G VINNI, 5G GROWTH, 5G SMART, 5G Solutions, 5G VICTORI
Energy	5G EVE, 5G VINNI, 5G GROWTH, 5G Solutions, 5G VICTORI
Health and lifestyle	5G HEART, 5G VINNI, 5G EVE, 5G TOURS
Smart cities/smart (air)ports	5G Eve, 5Genesis, 5G Solutions, 5G TOURS
Agriculture	5G HEART

One of the greatest contributions coming from 5G is the opening of possibilities for verticals that traditionally had to resort to custom-tailored network solutions (i.e., closed/independent topologies and/or protocols). Beside the overall performance increase, the traffic isolation resulted from slicing, and flexibility resulted from virtualization and other cloud-based technologies, expanded the deployment scope of cellular networks in verticals. Examples of this are the verticals coming from the Transportation, Energy and Tourism sectors in Europe, which are briefly described below.

Looking at the **Transportation sector**, particularly the Railway-driven businesses, involved communications are associated with important control-related mechanisms that govern vehicles, tracks, railway crossings and surveillance, amongst others. Such business considerations have a direct impact in user satisfaction and well-being, with zero tolerance for flaws (i.e., missed railway signalling can cause huge losses in material equipment and human lives). This is the underlying use case of the Transportation pilot in Aveiro of the H2020 5GROWTH project. Communications in transport systems are usually realized using dedicated cabled channels, linking sensors to control entities for train detection and level-crossing barrier opening/closing. Cabled links are also coupled with heavy-duty information protocols. The introduction of 5G allowed not only to assess the validation of a mobile network channel for the dissemination of transport information, but also to unlock new application scenarios (e.g., live 4K video of the current status of level crossings being streamed to oncoming trains).

Energy sector scenarios, also being trialled in Aveiro for the H2020 5GROWTH project, showcase important latency and reliability communications and their convergence with other kinds of traffic such as video surveillance and mobile maintenance crew AR/VR capabilities. Such integration allows distinctive scenarios such as low-voltage/medium-voltage substation monitoring and fault reporting, to actual reporting of time-sensitive alarms.

Both transportation and energy verticals have manifested expressive business gain at business model stage due to the landscape-changing characteristics offered by 5G with current trialling are contributing to promote full scale adoption within the sectors. It is important to take into

consideration that such sectors have long-duration innovation cycles, due to the safety requirements (both on machine and human aspects), and therefore adaptations cannot occur overnight. Additionally, both sectors have stringent requirements when it comes with heterogeneous slicing capability, mixing eMBB with URLLC needs, along with high-mobility (i.e., trains) and large coverage needs (i.e., railroad crossings and power substations existing in remote areas), which need further solutions beyond the scope of 5G.
With **Tourism sector** being one of the main data producer and consumer industry, 5G offers new possibilities to increase the competitiveness of this sector. Digital age tourists are always connected, which demands putting better connectivity infrastructures in touristic sites. Thanks to 5G, the connection for tourists is improved, remote spots in a destination can be shared on social media, and this connectivity increases the tourism experience, consuming and producing data that has a direct economic benefit in the touristic sites.
Further to the tourists visiting the sites physically, 5G enhances the usage of disruptive technologies as robotics, AR/VR allowing immersive experiences [2.4].
Connectivity also extend the smart cities by providing the possibility of remote working which makes destinations more attractive to combine leisure and work, and therefore the economic impact in tourism destinations.

2.7.2 China

Since China's 5G commercial launch in 2019, mobile operators, verticals, and technology companies have been working even more closely together to explore 5G use cases in vertical industries to empower their digital transformation. The ‘‘5G Verticals Use Cases for China 2020’ report by GSMA [2.5] describes 15 prominent examples of 5G-empowered applications for verticals, such as industrial manufacturing, transportation, media, logistics, electric power, healthcare, education, content creation. 5G vertical developments in China focuses into the practical scenarios, technical features, and development opportunities for the next generation technology. Most of these projects involve one or more mobile network operators (MNOs), China Mobile, China Telecom, China Unicom and vendors, Huawei, ZTE, Ericsson and Nokia with major vertical partners including China Southern Power Grid.

Since 2018, China has been hosting the ‘Bloom Cup’ 5G Application Competition[2] every year, representing the overall progress of China's 5G industry exploration. The latest one is the 4th ‘Bloom Cup’, which was held in September 2021. For the 4th ‘Bloom Cup’ more than 4000 projects across the country, covering government affairs, education, medical care, travel, express, media, tourism, finance, consumption and other fields join the competition, after more than a month of selection competition, 20 projects stood out into the final, finally determine 5 first prizes, 7 second prizes and 8 third prizes.5G ‘Bloom Cup’ competition focuses on five directions, which are industrial IoT, medical IoT, multimedia, energy IoT, and intelligent transportation (including ports and metros). The mining industry has become a highly popular one.

Industrial IoT is the key focus in China. Most projects involve machine vision and AI detection applications, which are the first batch of 5G application scenarios. The main requirement of the solution is that mobile edge computing (MEC) meets data security assurance and deterministic super uplink bandwidth, and new features such as 5G LAN of Release 16 are introduced. In terms of the industry ecosystem, industry convergence is accelerated, for example, the release of

[2] 4th competition application announcement [The 4th “Bloom Cup” 5G Application Competition officially launched (ccsa.org.cn)]

industry convergence white papers (such as steel and cement) and the establishment of joint laboratories/alliance.

The healthcare project accounts for 20%, second to industrial manufacturing, and is the focus of carriers. Telemedicine is the main service scenario, accounting for more than 54% of the total, and real-time remote consultation accounts for more than 57% of telemedicine. In terms of solutions, data transmission within enterprise networks and high bandwidth connection are the key content.

In the multimedia field, digital twin, 5G cloud extended reality (XR), and MEC technologies are converged, with 5G high-precision capabilities to form industry solutions, such as 5G smart business.

The energy IoT field mainly includes the electric power and mining industries. Power distribution networks are the most valuable 5G scenarios in the electric power industry. Virtual industry private networks based on public network slicing have become the mainstream solutions and have overcome the weaknesses of industry terminals, including 5G industrial routers, 5G timing CPEs, and 5G cameras. The mining industry mainly focuses on AI video analysis and monitoring and automatic driving.

Owners are willing to pay for the projects. A few key projects of smart grid, mobile health, smart factory, smart port, and multi-media have been continuously followed in the last 2 years. Most of the projects go through proof-of-concept (PoC), Pre-commercial, initial commercial contract phase, now come to the industry standardization and large-scale commercial stage.

In most cases, the industry terminals, security, industry standard, etc. would be blocking issues for large scale commercial use. For smart grid, the challenges of CPE and security have been overcome in 2020. Thousands of grid service terminals are expected to be commercialized in 2023-2025. For mobile health, the 5G medical group standards was released in 2020, and 5G medical industry standard subject has been successfully initiated in the National Health Commission. Also, medical device vendors provide various terminals with built-in 5G modules to meet 5G access requirements of Mobile ward round vehicles, mobile care vehicles, operating rooms, ICUs, bedside consultation vehicles for special patients, and remote video caravans. Hundreds of hospitals and factories have been covered by 5G indoor network. The mining industry has also become highly popular. However, the challenges for large scale commercial use still exist to find clear business operation entities, sort out the industry division of roles, and streamline supply and demand.

2.7.3 The United States

In the United States the plans of the major four MNOs – AT&T, Verizon, Sprint and T-Mobile – will determine the USA’s progress in 5G for verticals. They are quite diverse in terms of what they term ‘5G’, their business models, rollout schedules, and which parts of the spectrum will be used. Currently, however, the key efforts of MNOs in the United States have been rolling out different flavors of 5G for broadband access, including Fixed Wireless Access in 28 GHz by Verizon and mid-band enhanced mobile broadband access by AT&T and T-Mobile. In its recent White Paper, 5G Americas [2.6] has identified automation of vertical domains as a compelling application of 5G communication and has explored the use cases and requirements from the following domains: Rail-bound mass transit, building automation, factory of the future, eHealth, smart city, electrical power distribution, and event organization.

2.7.4 Other regions

Singapore has organized, with government backing, an important initiative for 5G as an industrial support infrastructure. The Info-Communications Media Development Authority (IMDA) is orchestrating the 5G effort towards a number of vertical industry sectors that are the main drivers of Singapore's economy – high technology manufacturing (semiconductors and digital device manufacture and assembly), technical services such as aircraft maintenance, and financial services. IMDA is supporting 5G vertical development with targeted pilots on campus sites such as factories and industrial zones in which the vertical sector, the equipment suppliers and the local operators participate. Japan has dedicated specific bands for private cellular networks by enterprises. The Ministry of Internal Affairs and Communications (MIC) in 2019 began working on the bands that local 5G (sometimes called local licenses or campus licenses) would use. They started with the 28.3–29.1GHz and 4.6-4.9GHz bands, and in 2020 made a slight addition, adding in 28.2 – 28.3 GHz. The manufacturing and education verticals lead the way with 13 and five deployments, respectively, followed by smart cities, urban rail, and intelligent buildings [2.7].

The UK's Industrial 5G Testbeds and Trials competition is making available Government investment to trial new 5G services and applications in the vertical industry sectors of manufacturing and logistics. The aim of these projects is to demonstrate the value of 5G, beyond enhanced mobile broadband, by targeting industrial uses that can help deliver efficiency, productivity, and other benefits in the economy.

3 EXPLORING 6G ARCHITECTURAL EVOLUTION AND BUILDING BLOCKS

Compared to the previous generations (2G, 3G, and 4G) where the main focus was on increasing the data rate of the mobile communication, 5G introduced a paradigm shift in the way that we look at the mobile communication systems. In addition to considering data throughput, 5G has incorporated the requirements of vertical industries in the big picture of mobile communication systems. One thing worth to mention is that although 5G set a group of requirements and nominal 5G KPIs, not all of them need necessarily to be met simultaneously for all use cases and scenarios. Maybe it is a bit early to understand how the foreseen 6G visions will be translated into the user experience, nevertheless there are some predictions available about how the future would be for the end users. Many scenarios are involving areas such as:

- Collaboration over Immersive XR (mainly Wi-Fi for indoor and 5G/6G for outdoor scenarios).
- Digital Twins (digital replica of living or non-living entity - a copy of anything physical that one can touch or a process or a place or a person or an animal, etc.).
- Hologram and Holoportation / ‘Holographic Telepresence’.
- Internet of Senses (especially smell and touch).
- Merged Reality (physical and virtual reality merged from both directions; digital objects will become parts of the physical reality while physical reality will become as transient as digital data).

These scenarios are found on a long list of materials published already about 6G. It includes visions coming from the major telecom vendors, pioneer mobile network operators (MNO), key user equipment providers, and leading research institutions in the world. However, it is worth to note that although there is a good common understanding between the presented views yet there is no confirmed and agreed 6G requirements, and many industry organizations are in the process of formulate 6G vision, e.g., ITU-R (IMT vision for 2030 and beyond)[3], NGMN [3.1-.2], etc.

This section discusses how architecture evolution could contribute to 6G vision, and its building blocks from different technical domains, which covers advanced radio technology, advanced network technology, integrated terrestrial and non-terrestrial network and impact of AI and machine earning solutions to the architecture evolution in the following sub-sections. THz Communications

3.1 THZ WIRELESS LINKS

3.1.1 Concept

In recent years, numerous THz wireless systems have been demonstrated with different bandwidth and technologies. Many of them produced 10 Gbps data rate, but in most cases the transmission was limited to short range, tens of meters, even with very high gain antennas, making them still not suitable for a wide deployment. The lack of relatively high-power transmitter is the main reason of short range.

[3] ITU-R Working Party 5D (WP 5D) starts the official steps for 6G vision and requirements contemplation in 2021. External Organizations (EO) are invited to provide views on for instance, application trends, IMT evolution, usage scenarios, etc.

Technology advancements have been substantial in developing chipset based on different processes such as CMOS, InP, GaAs, Si Ge and GaN. Each of them has its own advantages and limitation, but surely the low power electronic is well advanced and able to support multi-Gbps transmission. GaN is the most promising for high power, but presently limited to about 100 GHz.

Travelling wave tubes are under investigation for long range link both in point to multipoint and point to point, being able to produce more than one order of magnitude transmission power than a solid-state amplifier [3.3]. Antennas are evolving from simple small dimension horns to complex beamforming or beam steering configuration. In general, performance is comparable with microwave frequencies, with the advantage of a smaller footprint for the same antenna gain [3.4]. The small wave lengths in sub-THz and THz frequency range permits to implement antennas with thousands of elements in a small space, however the electronics is challenging due to the high integration complexity. This enables extreme massive MIMO and pencil beamforming and beam-steering [3.5], for Tbsp. data rates and to achieve good communication range. However, the electronics and baseband processing are highly challenging due to the increased complexity.

3.1.2 THz wireless links: challenges and opportunities

The future 6G wireless ecosystem cannot be realized without the exploitation of the high band spectrum (90 – 400 GHz outdoor and 90 – 1000 GHz indoor) [3.6]. The availability of ultra-high data rate with low latency everywhere is a main requirement to support a variety of data hungry novel applications. On one hand, the vast frequency bands available above 90 GHz would permit Gbps data rate at level of fiber. On the other hand, the technology challenge is formidable both in terms of propagation and equipment cost. Tens of dB of attenuation higher than microwave frequencies for the same link range require or higher antenna gain, or high-power amplifiers to satisfy the link budget. Line of sight and blockage free links need to be designed for avoiding outage and low availability. At the same time, the high attenuation permits an effective spatial division, frequency reuse and low interference expanding the potentiality of THz wireless networks.

The short wavelength (e.g., 3 mm at 100 GHz and 1 mm at 300 GHz) determines the dimensions of the electronic components, making fabrication and assembly difficult due to the small dimensions at the limit of fabrication technologies. The high manufacturing cost of THz equipment is a critical factor for its wide deployment. New and affordable technology approaches have to be introduced. At the same time the short wavelength permits low size antennas and components for high integration and low footprint, enabling an easier installation and deployment with high density in urban environment.

The high directivity of links and low transmission power make the control of radiation exposure easier, considering the high attenuation that ensures electric field well below the exposure limits as suggested by the regulation bodies.

It is worth mentioning that early in 2023 ETSI launched the Industry Specification Group (ISG) THz which concentrates on establishing the technical foundation for the development and standardization of THz communications (0.1 - 10 THz). The scope of the ISG THz [3.7] contains the definition of target scenarios and frequency bands of interest; the analysis of specific radio propagation aspects for THz communication, such as molecular absorption, effect of micro-mobility, specific considerations for scattering, reflections, and diffractions, and considerations for near-field propagation; the analysis of data from earlier measurement campaigns published in relevant literature; the performance of channel measurements for the selected scenarios and frequency bands; the development of channel models for the selected scenarios and frequency bands; the establishment of baseline for THz technology fundamentals, including antenna assumptions, simulation assumptions, and deployment strategies.

3.2 RECONFIGURABLE INTELLIGENT SURFACES

3.2.1 Concept

The modern field of metasurfaces builds upon earlier investigations on artificial surfaces reflect- and transmit-arrays at microwaves as well as planar periodic structures at optical frequencies. Most recently, in communication engineering applications, reconfigurable metasurfaces are receiving extensive attention in academia and industry as the fundamental building block to realize the concept of Reconfigurable Intelligent Surfaces (RIS), which are expected to play a role in beyond-5G and 6G mobile communication systems.

RIS is a programmable structure that can be used to control the propagation of electromagnetic waves by locally changing the electric and magnetic properties of the surface. Compared with traditional technologies (i.e., relay, MIMO, etc.), RIS offers many advantages including low deployment cost and passive communication to meet green requirements for ubiquitous deployment, and yet needs to be tested in practical settings. RIS can be used to enhance traditional communications, such as NLOS transmission and edge user coverage. It can also support more new applications, such as UAV Communications, high-precision positioning, passive IoT, secure communications, etc. More specifically wireless propagation intelligent reconfiguration through a reasonable design of reconfigurable RIS elements, a higher capacity and coverage of wireless network can be achieved. A real-time reconstruction of the propagation, control of the wireless environment through passive reflection signals, control of energy at transmission and reception, reduction of interference, offering a greater transmission capacity and higher spectral efficiency are among advantages of the RIS technology.

The RIS is mainly considered to be a of interest for systems operating at frequencies from tens of GHz to THz. In particular, in transmit- or reflect-array configuration it can operate as an alternative to the conventional analogue, hybrid and digital beamforming, and this has important advantages such as less energy consumption and reduced complexity for frequencies above 100 GHz [3.5]. Furthermore, at these frequency bands, the signal propagation is heavily attenuated and can be blocked completely by the obstacles in the propagation environment. In these cases, the ability to form beams with moderate sized surfaces enables communication between the TX and RX [3.8] By placing intelligent surfaces in the environment where wireless systems are operating, the properties of the radio channels can be controlled at least partially.

3.2.2 Activities

Many activities have been set up to progress research initiatives, standardization and industrial implementation of RIS.
ETSI has recently launched a new Industry Specification Group on Reconfigurable Intelligent Surfaces (ISG RIS) [3.9]. The group has been created to review and establish global standardization for RIS technology. In October 2021, ETSI launched an Industry Specification Group (ISG) on RIS (ISG RIS)[4] to review and establish global standardization of the technology, with a focus on mobile communication systems. In particular, it was established to consider a new type of system node with surfaces providing reflection, refraction and absorption properties

[4] https://www.etsi.org/committee/1966-ris

through multiple small antennas or metamaterials elements, which can be adapted to a specific radio channel environment.
The ISG identifies and describes RIS-related use cases and deployment scenarios, specifies requirements, and identifies technology challenges in areas including fixed and mobile wireless access, fronthaul and backhaul, sensing and positioning, energy and EMF exposure limits, security and privacy. It also documents a networking end-to-end reference architecture including RIS elements, describes RIS-based specific deployment guidelines, provides a gap analysis for RIS microelectronics and enabling technologies and develops proofs of concepts.

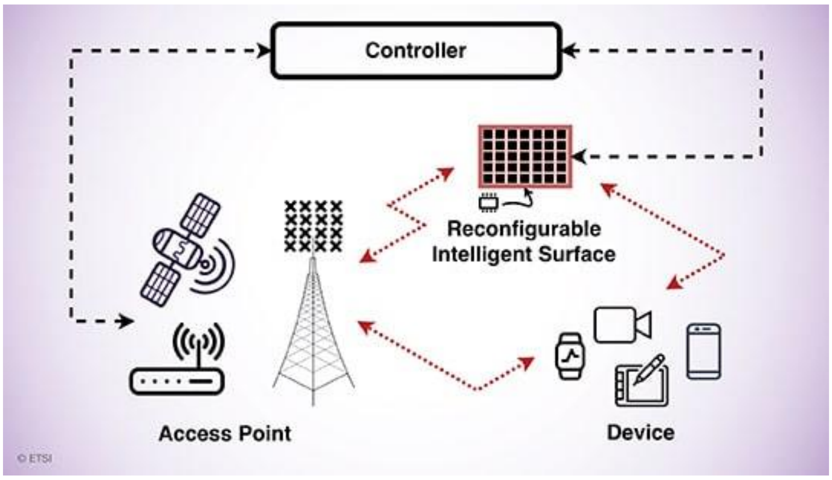

Figure 3.2.2-1 Scenarios for future deployment of RIS a new relay element[5]

In 3GPP, the RIS project was extensively discussed. But no approval was reached in the first version Rel-18 of 5G-Advanced. A preliminary consensus to set up the project in the second version Rel-19 has been met instead.

China's IMT-2030 promotion group recently published the result of their study covering 6G vision, driving forces of 6G development, candidate use cases of 6G, ten candidate 6G technologies, and expressed some thoughts on the 6G development. RIS was seen as a promising technology. Consequently, some initiatives were started. In June 2020 the wireless technology group 'RIS task group' of IMT-2030 was promoted by ZTE in cooperation with Southeast University and other units. IEEE ComSoc, a global community of engineers, practitioners and academics working together to advance communications technology for Emerging Technologies Initiative on Reconfigurable Intelligent Surfaces (ETI-RIS) was established in August 2020. In September 2020, Chinese vendors and MNOs established the 'RIS research project' in CCSA TC5WG6 and launched the 'RIS TECH Alliance (RISTA)'[6] promoted by industry and academia jointly. In September 2021, IMT-2030 (6G) Promotion Group officially released the industry's first research report 'Research Report on Reconfigurable Intelligent Surface (RIS)'.

[5] Source: ETSI https://www.etsi.org/newsroom/press-releases/1979-etsi-launches-a-new-group-on-reconfigurable-intelligent-surfaces
[6] Source: http://www.risalliance.com

3.3 Advanced Network Technology Trends

3.3.1 Architecture

As we look ahead in the rapidly-evolving technology landscape, it is clear that IoT, AI, and edge computing are key components of the future digital society, emphasizing the fact that competitive advantage in the future digital world is based on the ability to innovate rapidly and continuously improve an offering through software- and, increasingly, hardware-defined experiences, not to mention better services. Challenges like interoperability, data trust and ownership, latency as well as energy efficiency and being green have to be carefully and jointly addressed.

In practical terms, reviewing the technology progress so far could put light on how to better select the direction of crafting the blueprint for the future. To build a holistic view, we try to simultaneously keep track of three main technology domains: cloud, networking, and IoT enabled application sectors (e.g., mobility, logistics, manufacturing, energy and other utilities, buildings, or farming). Traditionally, the solutions were developed in an expensive, non-scalable, inflexible and slow to market model. Cloud domain was probably the first sector to move into a future model by introducing serverless, decentralized and edge computing. It allows users to run code without provisioning or managing any underlying system or application infrastructure, and they automatically scale to support increasing or decreasing loads. It is easy to deploy, low cost, scalable, improved latency, greener, ubiquitous and flexible. Thanks to this, the way applications are hosted, architected and managed changed a lot over the past 30 years. Meanwhile, networking technology has evolved a lot. Networks have been getting better (i.e., more reliable), faster (bandwidth capacity grew exponentially), easier to manage, and the protocol stack got stronger. Today’s networks are composable and modular, are used on-demand, moving towards limited or eventually no need for traditional MNOs (private networks), grants beyond the best effort delivery with higher security and remains up to date all the time, and finally automatically scales (up, down, etc.) and managed (zero-touch) heading towards realization of a networkless vision. Concretely, the pre-established, pre-configured, always-on, resource-consuming network fabric could instead be replaced by an on-demand instantiated, composable and modular, integrated set of network resources. This would enable a new kind of economy of scale, as custom-tailored communications could take advantage of network slicing and virtualization infrastructure isolation principles to provide Pay-as-you-Use network models, supported by dynamically composable networks. These networks would live for the duration of the necessary connection, benefiting from automation capabilities imprinted in the network, along with other serverless correspondents such as automatic scaling and intrinsic security.

At the same time, the way we share and govern data on the decentralized and distributed cloud-edge-IoT continuum ecosystem has evolved radically. As stated before, initiatives such as GAIA-X develops common requirements for a European data infrastructure. Given that the crucial component in this ecosystem is decentralized communication mechanism by which devices can exchange data and send commands between themselves, a common open, transparent, scalable and trustworthy data sharing is a key enabler to realize mesh networking over the cloud-edge-IoT infrastructure, aiming to remove many of the roadblocks to achieving impactful economic visions such as Industry 4.0, smart cities, smart mobility and logistic, etc.

There are a number of technologies which may drive enhancements on 6G network architecture design compared to the previous generations [3.10]. For example:

- The introduction of spectrum sharing and new spectrum bands might cause changes. Small cells introduce more and novel cells in the network. It could cause issues for the current network architecture, since the network might force to handle several more orders of entities than before. For example, the introduction of new spectrum bands, e.g., THz, could cause changes on the Radio Access Network (RAN) technologies and protocols. Also, those THz resources needs to be managed for particular services by the core. It is important to define proper ways to manage those resources. At the same time, the current functionalities of the mobile core network such as the way that network slicing is carried out might need to be changed to fulfil the spectrum sharing requirements.

- New network topologies and introduction of other networking solutions like non-terrestrial networks (e.g., satellite) and optical solutions will impose changes on the mobile network. Each of these systems have their own system which have been developed isolated from the mobile network. Interfacing between the two and ultimately merging them into one single entity, being able to seamlessly control and manage several technologies simultaneously, is a big challenge to address.
- Introduction of AI/ML is a big change compared with the traditional mobile networks. The key here is to build up a mutual relationship between AI/ML solutions and networking technology either as integrated or over the top solutions. The future asks for a network-native AI/ML incorporation. Just ‘using’ AI/ML is not the point. Interesting aspect is that faster networking allows you to build faster AI, which can better steer flows, etc. That produces a speed up beyond what they could do when taken alone. However, further research is required to make AI distributed.
- The path started by Zero touch solutions, full automation, self-governance, sustainability considerations are some key directions for the system operation and automation that needs further investigation.
- Incorporation of cybersecurity by design, privacy awareness, GDPR compliance, human in the loop concepts on the mentioned information and network security are key directions to go.
- The introduction of support for edge computing into the mobile communication network was a big step forward in 5G. This trend of disaggregation will continue in 6G, extending the edge concept into deep / far edge and IoT devices. RAN-Core convergence, distributed mobile edge computing coordination, far edge and fog computing, data interoperability, computational offloading, swarm computing, and trustworthiness are among the hot topics in this line.
- High precision networking as well as localization and RF-sensing are key topic for 6G which enables many vertical use cases. Mobile functionalities and protocols should evolve in a way to provide higher precision. It also enables new uses for mobile network, e.g. prevention, detection and mitigation of GPS spoofing attacks. These types of usage of mobile functionality were not foreseen in 5G.
- Incorporation sensing devices and communication is a new direction that the mobile systems is pursuing. If we accept this view, next generation of communication should support internet of senses. Here ‘sense’ could be a broad and wide term ranging from visual, hearing and touch to tasting. It is a very forward-looking vision and it is not yet clear how much change it might cause to the network as we know today.
- Extreme connectivity/networking and ultra-low latency definitely means enhancement of network and user plane and control signaling procedures, protocols and functionalities.
- Industrial IoT is a key point to be addressed in 6G. Business wise this sector seems to be the killer application of 5G and 6G since it doesn’t need nation wide deployment and the clients are private sector customers. It makes Industrial IoT a key focus area for the uptake of the 5G/6G mobile telecommunication systems. We are seeing a good support

from the governments also to dedicate spectrum for IIoT scenarios within their territories. This item will definitely expose changes in the way that mobile networks work. We can list a long list of here but just as an example, time sensitive networking (TSN) could be a first step to take in this direction.

- Non-public networks (NPN) is a key area for the future. With a good margin, we can expect smaller private clients become the NPN operators, e.g. on manufacturing sites. Federation of NPNs as a new deployment vector for public networks (PN), e.g. as a virtual slice in those NPNs, is indeed a very interesting path. NPN proliferation is the revolution leading to 6G.
- Incorporating compute as part of the resource pool in networks and understanding it as such, including for the fundamental, initial networking tasks and for the fundamental initial compute tasks at the same time – this is a revolution of the distributed computing. If this comes, then 6G will become a highly localized, context-aware cloud at the tip of your fingers, naturally incarnated in the same context as the user asking for services, whatever these are, XR or something else. To name some more in deep changes in this direction we can include Cloud-native networking and RAN-core convergence. It could expose changes on the networks, e.g. on the possible new functional splits and the introduction of new interfaces. However, with the current direction of the technology it seems more like a deployment and implementation problem.

To enable challenging vertical applications that cannot be supported by 5G – either in terms of their requirements for network performance or emerging aspects such as sustainability or information security – future networks should not only enable more efficient transfer of bits, but also address the trade-off between performance, energy efficiency, and trustworthiness. In addition, the networks should aim at providing a holistic platform for the variety of the services, including the communication itself.

Currently, the evolution of the 5G systems is paving the way towards a 6G architecture in terms of softwarization of the RAN and core network functionalities, adoption of service-based architecture approaches, as well as virtualization of the system components. 6G networks are thus foreseen to be a mix ecosystem composed of NPNs and PNs, software-oriented, flexible and trustworthy platforms that are essentially enabled by AI-based management of computational resources and network functions. In 6G, the whole network can be perceived as a distributed computer with embedded secure, trusted, and tailored communication services. This vision is very much in line with digital transformation view promoted by Industrial Internet Reference Architecture (IIRA) [3.11] where ‘serverless’ and ‘networkless’ concepts come together to form a single ‘service platform’. 6G mobile connectivity become part of the ‘Platform Tier’ and ‘Edge Tier’ in an easy to use, everywhere present and affordable for all. Soon the mobile connectivity will become an integrated part of our digital society in a more democratized way, open for big (e.g. MNOs) and small players.

This implies various changes to the current networked system architectures, as the complexity of the whole system is increasing with the decentralization and distribution of the network functionalities. This makes the maintenance and management of the system an increasingly challenging task, leading to higher operational costs and making the system more error prone. Therefore, higher degrees of intelligence and automated management of the next generation networks is needed than what has been achieved in 5G.

With the increasing demand for automated and intelligent network management, it is foreseen that the development of software oriented service-based architecture (SBA) for telecommunication systems evolve towards agent type of virtualized micro- and nanofunctionalities. Meanwhile, it is important to acknowledge that the design and orchestration of agent-based distributed self-organizing networks is not easy. A certain level of hierarchy is still needed for efficient optimization and use of resources. Loose or weak coupling [3.11] is a promising approach for self-organization as it solves the stability, efficiency, and complexity problems associated with such systems [3.12]. In addition, various strategies may apply for zero-touch orchestration of the micro- and nanofunctionalities, such as swarm technologies and networks and cellular automata strategies, which enable target setting for automatized system optimization. Finally, intelligent radio access control and distribution of RAN units and functional splits, will be the first step towards the 6G systems in terms of decentralizing the radio access network's control and management. It is expected such changes make 6G networks more ready for various vertical sectors, especially in the form of non-public networks and soon we will witness the uptake of these modern technologies in key verticals such as manufacturing.

The new trends of composing network functionalities as a chain of virtualized microservices or functions and distributing them over the heterogeneous communication and computing resources naturally also impacts the way, how vertical applications, planned to operate over the future networks, should be designed and implemented. In this respect, the internet has already seen a transition from the traditional client-single-server architectures towards the clients communicating with large data centers that are acting as a point of presence [3.13]. This way, the service providers have been able to host services without a need to possess or operate their own resources. Moreover, the model essentially allows bringing the services and content closer to the end-users for better performance and scalability, as has happened with many media and social media type of over-the-top (OTT) services thanks to content delivery networks (CDN). Currently, the trend of virtualizing and distributing applications and their functionalities according to the microservices paradigm and utilizing container-based light-weight virtualization technologies such as Docker and Kubernetes are allowing them to better utilize and adapt to the communication and embedded computing resources of networks more efficiently. Yet, more lightweight and flexible solutions are likely to be needed, as well as integration of application-level intelligence regarding the communication and computing requirements into the AI-driven network system optimization, for the vertical applications to be able to fully utilize and benefit from the 6G capabilities.

3.3.2 Resource management

Besides the service development practices, at the management level, the adaptation of the Cloud Native into telecommunications systems pushes for full automation operations in network and service automation is an emerging concept that promotes minimizing human intervention. The purpose is not only to eliminate errors, but also to introduce agility in the system and reducing the cost. Closed-loop automation depends heavily on artificial intelligence. AI is used to evaluate the current resource status and current service status, and more importantly, to predict any future problems. AI is used to decide how to react to current or predicted status changes. AI is also used to optimize the delivered service to avoid unprofitable waste of resources. At the same time, it is crucial to protect the network and system assets against potential cybersecurity risks introduced by the unprecedented evolution of the threat landscape. Zero touch automation also helps on the dynamic management of trust chains running end-to-end and enabling critical workloads to traversing different tenants and stakeholders with the required level of security and trust. This concept has to be fully integrated by design on the Cloud Native telco management solutions with the help of emerging technologies such as zero-touch network and service management, software-defined security models, Distributed Ledger Technologies (DLT), zero trust models, and trusted execution environments.

Although closed loop automation, with limited human intervention brings all the promise of a fully automated business, one of the main ongoing philosophical debates is to consider a role for human in the loop. The issue raises from the concerns about trusting a full automated system.

Humans in the loop (HITL) inspects, validates, and makes changes to algorithms to improve outcomes. They could also collect, label, and conduct quality control on data.

3.3.3 AI and Machine Learning

After continuous development of artificial intelligence (AI) technologies such as deep learning, reinforcement learning, and federated learning, etc., AI is now considered to be a new general-purpose technology which has rich technical capabilities and wide usage scope in diversified scenarios. Its benefits will far exceed consumer businesses, covering the entire economic landscape and affecting all aspects of our society. In the 6G era, the development of AI technologies can accelerate the development of every industry and lead to significant industry changes.

For AI technology, there are three essential pillars: (1) Data: it is the key asset of the entire industry and it is considered as the new oil. All types of AI applications/services need to collect various types of data, perform the analysis and apply the corresponding results to execute particular behaviour like a set of actions. It is envisioned that more and more data (especially industry data) will be processed at the edge due to security and privacy concerns. A communication system that could capture such requirements and at the same time provide full compliance of policies is very essential. (2) Computing capability: it provides the fundamental support for the AI industry. Edge intelligent, as the new synergy, could bring many advantages as well as challenges for resource scheduling and service deployment. For instance, a high-performance platform is required to effectively organize distributed and heterogeneous resources from multi-parties and meanwhile support elastic scaling up-and-down, in-and-out. (3) Algorithm: it is the soul of AI services, which defines its application scope and serving efficiency. Communication system itself does not know how AI algorithms are defined, but it could provide a better support for running such algorithms. For instance, deep learning algorithms are highly dependent on communication infrastructure, which may relate to the algorithm scalability, bandwidth requirement and ultra-low latency or even real-time requirement. Hence network system architecture design may influence how AI algorithm is trained and how AI inference is performed.

When AI services could be natively provided by the mobile communication system, it will transform its provisioning model, i.e. from Cloud AI to Network AI. For Cloud AI model, data is gathered all over the system, but the training and inferencing are performed in a centralized location, usually in a power-intensive datacentre specialized for such computations (special hardware, etc.). The widespread deployment of AI in various industries poses strong requirements for future wireless networks with new basic capabilities, such as large- scale distributed training, real-time edge inference, native data desensitization, etc. This is driving us to explore how 6G networks can be built as a platform that natively supports AI training and inference, and provides AI as a service (AIaaS) for a vast line-up of AI applications. Network AI refers to this very concept. It is a native intelligent architecture that deeply integrates communications technologies, information technologies, data technologies, and industry intelligence into mobile communication networks [3.14].

3.4 AI SERVICES

The AI services are developed to perform specific tasks, which are widely adopted by vertical industries, including finance, healthcare, education, transportation, and more. The use cases cover a wide range of activities including medical diagnosis, electronic trading platforms, robot control, and remote sensing. By promoting Network AI concept, it is important to understand how network could support specific AI usage scenarios.

Federated learning

Federated learning enables multiple participants to build a common, robust machine learning model without sharing data, thus allowing to address critical issues such as data privacy, data security, data access rights and access to heterogeneous data. Its applications are spread over a number of industries including defence, telecommunications, IoT, and pharmaceutics.

In federated learning, participants use their local data to cooperatively train an ML model required by a federated learning server. Participants then send the model updates, i.e., the model's weights, to the federated learning server for aggregation. The steps are repeated in multiple rounds until a desirable accuracy is achieved [3.15].

Distilled learning

The great success of deep learning is mainly due to its scalability to encode large-scale data and to maneuver billions of model parameters. However, it is a challenge to deploy these cumbersome deep models on devices with limited resources, e.g., mobile phones and embedded devices, not only because of the high computational complexity but also the large storage requirements. To this end, a variety of model compression and acceleration techniques have been developed. As a representative type of model compression and acceleration, knowledge distillation effectively learns a small student model from a large teacher model [3.16].

Transferring the knowledge from a large to a small model needs to somehow teach to the latter without loss of validity. If both models are trained on the same data, the small model may have insufficient capacity to learn a concise knowledge representation given the same computational resources and same data as the large model.

Real-time AI inference

AI services are normally computation-intensive, memory-consuming and power-consuming. Meanwhile mobile devices usually have stringent energy consumption, compute and memory limitations for running a complete offline AI inference on-board. Many AI services, e.g. image recognition, offload the inference processing from mobile devices to a cloud AI server. However, the cloud-based AI inference tasks need to take into account the computation load at the data centre, required data rate/latency, privacy protection requirement, etc. [3.17]. Many works [3.18-19] have shown that inference for real-time AI services (e.g. image processing) with device-network synergy can alleviate the pressure of computation, memory footprint, storage, power and required data rate on devices, reduce end-to-end latency and energy consumption, and improve the end-to-end accuracy, efficiency and privacy when compared to the local execution approach on either side.

3.4.1 Challenges and future research directions

It is envisioned that, future mobile communication infrastructure will be responsible to provide 'Intelligence Inclusion' that could be benefited by the entire society. Therefore, it gives the prerequisite for the 6G system architecture design: native support for AI service [3.20], which will bring the system architecture innovation from the following aspects:

- **Computing and communication convergence**

To handle intelligent services, it is not only about orchestrating and managing communication resource, but computing resource at the same time. This brings new research challenges on end to end resource management and run-time scheduling. Moreover, such computing resource is not only at the core network, it may also be further extended to the deep edge.

Converged computing and communication may raise new requirements on RAN architecture design as well, especially to embrace heterogeneous resources at the access part which is organized in ad hoc manner.

- **Data management**

Data is the key asset to provide intelligent services. In next generation mobile communication system, the amount of data types will increase to another level of magnitude, which will cover from terminal to network equipment, from environmental information to network service, from B2C type to B2B type. Therefore, the data management scheme could be very different compared to 5G, which may require system-level design instead of conventional telco database service. As a matter of fact, 6G system in a sense should be empowered like a dataspace (an abstraction in data management that aim to overcome problems encountered in data integration). The data to deal with in the mentioned dataspace could range from the telecommunication system originated data as well as data generated and used by verticals and applications. 6G dataspace should be able to ensure foundational principles such as FAIR (Findability, Accessibility, Interoperability, and Reusability) [3.21], General Data Protection Regulation (GDPR) [3.22], privacy and sovereignty. In a view, 6G should be a marriage between the previous good works done on initiatives such as international data spaces [3.23] and GAIA-X [3.24], landing them on the mobile communication domain and its cloud-edge continuum.

Also, the information silo problem has to be tackled properly. Data, information and services are not offered necessarily in a standardized way and that results in information silos. Already within one and the same entity (company/business/network), different sources of data are used (technical/business). When this data is homogenized so that is can be accessed via a standardized interface, added value services like digital twins can be offered which can provide extremely important values (e.g. predictive maintenance, carbon footprint monitoring and reduction, sustainability forecast, etc.). There were several paths to solve this issue. Probably, one of the most promising ones is to use Asset Administrative Shell (AAS). The AAS offers a standardized way of providing and accessing information and thus helps overcome the information silo problem. By following a single standard, all industries (telecom sector and especially end users), benefit from an open and standardized meta-model, standardized data models with homogenized semantics (e.g., technical and operational data) and standardized APIs and infrastructure services.

We could envision that, it shall be a unified and efficient data governance framework which could efficiently collect, organize, desensitize, store and access data, meanwhile, it is also capable to provide reliable and trustworthy data services towards third-party entities.

- **AI and ML orchestration and management (O&M)**

Native AI provisioning from mobile communication system requires orchestrating, managing, and scheduling E2E network AI services and related resources (e.g. communication and computing resources). For instance, in [3.20], such concept was first introduced as the network AI management and orchestration (NAMO), which contains two aspects:

- AI service O&M: it manages the entire lifecycle of AI services, e.g. focusing on parsing and orchestration of network AI services, as well as the relevant status. Administration policies could be issued to add, modify, and delete logical and physical AI workflows.
- Resource O&M: focusing on mapping AI services/workflows to specific resources for execution (e.g., a graphical processing unit, a network connection, etc.). Such communication and computing resources could be heterogeneous and distributed.

- **Trust and security**

The future networks are seen as software oriented, flexible, and trustworthy platforms, driven by AI-based instantiation and allocation of computational resources, network functions, applications, and services for specific verticals and use cases. The 6G networks are seen as holistic service platforms, where connectivity is one of the services [3.25]. Thus, network is like a distributed, loosely coupled, computer or better said a distributed smartphone, with embedded efficient, secure, and trusted mobile communication services.

The variety of vertical use cases and critical system require already today highly secure and trustworthy communication and platform to run the functions and services like data processing, data storage and computing, which cannot be met by current network security solutions. When considering 6G as a general-purpose technology, which can be applied verity of use cases and vertical segment needs, also the security needs to be seen as software-defined component, which can be intelligently adopted to specific use case and system needs. In addition, the security and security enablers need to be considered already in system design phase and not as a separate add-on for system. Thus, we speak about software-defined security by design.

It is essential that the trustworthiness can be guaranteed throughout the whole communication platform and for all the system components, which are interconnected locally or globally. Ensuring the trustworthiness of communication and connectivity platform will be one of the main challenges also for the future research. At the same time, when tightening the security constraints, we should take care of the trade-off between performance, energy efficiency, and security when optimizing the network. Finding the balance between these attributes for use case specific network slices, and means how to arrange security without compromising, e.g., system performance, dependability, or service accessibility are essential.

We can also say that the network is an amalgamation of extremely dense micro networks with varying number and type of devices, highly diverse floating system components and services, which needs to be instantiated and orchestrated on demand for different purposes. In such architecture, for example, the in-network data processing and caching are natively inbuilt features, increasing the complexity of system and creating demands for enhanced security features for both control and data plane. The complexity of distributed software-based architecture and decentralization of core functionalities and application as well as orchestration of the components and AI driven the optimization of system, create far larger attack surface than todays' systems have.

To manage with the large attack surface, it is already now seen that AI is needed. The role of AI in the domain of security is already now increasing and will increase even more in future. We have been using AI and machine learning in various ways to improve the network security, e.g., in traffic anomaly detection, intrusion detection, spam filtering, radio resource management, spectrum management etc. For 6G network, some of the key targets for AI would be; efficient orchestration of security components and functionalities in security architecture, preserving privacy of users and user data, how to differentiate noise and interference-based corruption of data versus security attacks in complex network, integrity verification of raw-data, security monitoring of encrypted data, automated treat intelligence and prediction, and for example identification of synthetic media. The research needs to be carried out to find on one hand, how artificial intelligence and machine learning can be applied to improve the security, and on the other hand, how AI can be used to compromise other AI algorithms or fingerprint the weaknesses of other AI-based security approaches. Thus, AI-based approaches need to be further researched also to self-test, protect against revealing vulnerabilities, and adopting self-healing procedures. AI-steered fuzzing, for example, was demonstrated in network [3.26]. As we speak about the highly tailorable system, also the AI enablers for security needs to be considered in system design phase and enabled as part of software-defined security architecture.

As discussed in previous section on AI and Machine Learning, the federated learning is foreseen as potential candidate for efficient telecommunication system optimization, such as radio access network and spectrum management. In the cases where the system itself and resource control is distributed, the distributed learning algorithm can be also applied. However, for example with federated learning in which the global model is built based on updated parameters from local models and feedback look from global model for each local learner is needed, there are also potential vulnerabilities foreseen. How to avoid for example the model-poisoning attacks and membership inference attacks in federated learning are still to be studied especially when applying in different parts of telecommunication system. Some considerations on machine learning threads for mobile network security, which are valid concerns also for 6G, have been discussed earlier for example in [3.27].

The privacy is another attribute which needs to be considered in system design, thus we can also speak about privacy by design. As already today, users and services will be intertwined digitally, resulting in higher requirements of privacy after digitally proved trust establishing mechanisms. Thus, monitoring and safeguarding the 6G ecosystem will require radically new thinking and technological solutions from the perspectives of privacy and security. We can also think how we can leverage the earlier research, e.g., on Content Centric Networking (CCN)/ Named Data Networks (NDN) and Information Centric Networking (ICN) to enable trustworthy, protected end-to-end communication and in-network processing in complex network of micro-networks and microservices. In addition, the advances on blockchain technologies and new architectural solutions for Internet are to be considered.

In contrast to current trust network consideration where we state and define if network (e.g., corporate intranet) is trusted or not, or e.g., to ICN principles, where networked devices are untrusted, but data and packets itself can be trusted, the Zero Trust security model, introduced by John Kindervag in 2010 targets is to eliminate the whole concept of trust. In practice, this means that idea of trusted and untrusted networks does not exist, and all the network traffic is untrusted until it is verified, inspected, authorized, and secured. When we have a perfectly secure system for the specific purpose, we can say that we would not need the concept of trust for that specific system perimeter. The target for 6G will be on enabling the trustworthiness of the platform for each specific purpose it is targeted. Considering how the Zero Trust security model has been defined, it has similar features than, e.g., ICN, in which the data packets in network are already verified, authorized and secured at end points. It can be said that from the data or end-to-end service point of the view, the system is perfectly secure and trustworthy even it is not possible to trust each actor or component in network.

In practice, the Zero Trust -concept introduces so call protect surface, which is defined from network's most critical data, assets, applications and services. In a way, in telecommunication system it is a representation/blueprint of network slice including critical system functions and data of, for example, corporate infrastructure. When such protect surface is defined and users, services, data and infrastructure are identified, a micro-perimeter is enabled with specific segmentation gateway. This micro-perimeter is in practice a software firewall, which monitors and enables traffic or application to and from protect surface. The micro-perimeter itself need to move and follow the protect surface. In the telecommunication systems, the similar idea has been introduced and carried out, e.g., in mirco-segmentation concepts [3.28]. The micro-segment defines and implements the sub-slice the network, which can be used to protect the critical system services and functionalities or for countermeasures for security attacks. In 6G such dynamic operations to ensure security, needs to be in-build in architecture, zero-touch management of Zero Trust and micro-segmentation needs to be implemented for critical components/services of system, with seamless mobility of mirco-perimeters/micro-segment within the network slice and protect surface. Would it be possible to combine Zero Trust and, e.g. ICN security models and what would be the impact of those for system performance and sustainability point of view, could be addressed in future research for different vertical use cases.

Cryptography is of course one important way to enable security and protection of privacy data and information. However, there already now challenges to provide strong enough protection encryptions for all the critical data and connections. This threat is not really due to current encryption algorithms, yet, since, e.g., with large enough key space (e.g. 2048 bits) even the widely used Rivest-Shamir-Adleman (RSA) public-key cryptosystem will provide well protection for brute force attacks with today computers. We can assume that in the near future an adversary may have access to quantum algorithms, which break the conventional cryptography, especially asymmetric cryptography such as RSA. The symmetric-key cryptosystem, Advanced Encryption Standard (AES), however, is too strong to crack, unless the key is not known, even with much shorter keys than RSA. Today, it is foreseen that the quantum computers, which could be used to crack the public-key cryptosystems are still far in the future. The post quantum cryptography would be essential to adopt to secure the information in future generation of communication systems. However, it would be important to consider already from 6G security architecture point, how to support such PQC algorithms, even though the treat for breaking the even RSA is not imminent. At this stage and for 6G, hybrid solutions could be considered, which would allow to support both classical and post-quantum encryption. Considering the 6G security architecture, the development should target to enable flexible and efficient use of different methods and protocols depending on the purpose. More important thing is that the key lengths will be kept long enough and the keys are protected. For this, the system needs to be hardened to prevent any leaks of information, and the hardening needs to be carried out in various system levels from mobile communication service functions to data services and data bases and users' interactions.

The problems have arisen also from possibilities to eavesdrop the communications, for this quantum key distribution (QKD) was proposed already decades ago. The studies of potential algorithms for quantum cryptography and key exchange problems have started already at 70s and 80s [3.29]. In Europe, the study and design of future European quantum communication network has started within, EuroQCI (European Quantum Communication Infrastructure) initiative. The target for this is to build Europe-wide network of trusted nodes and optical infrastructure for basis of a quantum Internet in Europe. The first services, which can be enabled with infrastructure include the QKD services, e.g., to secure the distribution and delivery of critical data. In addition, for terrestrial fiber network, the EuroQCI includes also the space-segment to ensure full coverage across the EU and other continents. The target in first place is to enable security for critical infrastructures and institution against cyber threats. When considering the 6G and future networks, which are to serve variety of critical infrastructures, also research on how the quantum Internet can be applied for 6G system needs to be carried out. How can QKD and quantum Internet improve the security of future highly distributed and decentralized telecommunication system?

- **New KPIs and evaluation methodologies**

In 6G, joint computing and communication consideration is important for compute-intensive type of network services. Due to the emerging of new services (e.g. AI), new evaluation methodologies and new KPIs need to be brainstormed upon conventional schemes, which is performance evaluation oriented. For example:

- New KPI schemes to evaluate system's capability to provide heterogeneous resources for communication and computing (including performance, energy consumption, sustainability, etc.).
- New KPI schemes to evaluate the performance of provisioned intelligent services (including inference accuracy, learning convergence time, resource usage efficiency, etc.)

3.4.2 Cloud native and softwarization

The adaptation of cloud/edge continuum in the telecommunication domain calls for more efficient and automated ways to develop, deploy, maintain, manage and update services based on the vertical needs. It demands several changes at different levels in the way that we treat edge computing capabilities and we mange services across the network.

Due to the evolution in virtualization technologies and networking, a new paradigm has arrived in the telco domain, the Cloud Native telco. This means a radical new approach to NFV, crucially needed to meet verticals requirements and lower deployment and operational costs. The only feasible approach for the Cloud Native Telco is to offer an evolution of Virtual Network Functions (VNFs) running in VMs towards Container-based Network Functions (CNFs), running in containers. It mirrors how enterprises are moving their monoliths based on VMs to containers orchestrated by Kubernetes and then (often slowly) refactoring them into micro services.

5G was an important catalyser in leveraging cloud technologies into the telco arena, with the introduction of Software Defined Networking and Network Function Virtualization concepts, originating efforts under the scope of ETSI NFV, amongst others. Despite the growing tight coupling between these two worlds, the cloud arena has been progressing on its own, and thus the uptaking of relevant technologies, despite providing new possibilities, might require as well new ways of thinking on how traditional telecommunication-based procedures use to operate. We are currently witnessing the shift from fully fledged virtual machines to container clusters, and the usage of microservices as an architectural design trend for applications that are able to run on-demand and in response to previously configured stimuli, or serverless. The next breakthrough, even though already amply in deployment under the cloud-world, follows the Big Tech[7] companies addressing the focus on business agility by fully integrating the underlying digital ecosystem that composes the cloud-services themselves, as tools for building the intended services, applications or functions developed under a cloud-native principle. However, in order to fully leverage cloud-native it is important to rewire the way of thinking network functions, building them over the underlying fabric of the cloud, as well as leveraging the cloud service provisioning tools for speed, safety and scale. This demands a comprehensive architectural system redesign which, despite its initial cost, will see increased benefits associated to unlock the full potential of the cloud, namely globalization, scalability and unprecedented dynamism. Important aspects such as reducing functions' development cycles, and promoting active innovation, development and deployment without impacting their operations. This capability demands that the architecture of a network service becomes able to be decomposed into isolated components (i.e., independent databases, API's) while still being bounded at the inter-component level through event-based persistence (i.e. message streaming). This aspect allows failures (or downtimes due to upgrades/updates) to not force the whole system to be shutdown. In fact, when such entities come back up, they can rely on the message streaming logs present in the event persistence to quickly regain state and operate. One of the other true potential aspects coming with cloud-native architectural design is the growing

[7] Big Tech companies encompass Google, Amazon, Facebook, Apple and Microsoft and can even follow multiple denominations such as GAFA; GAFAM, FAAMG or FAANG, depending on which companies belong to the group composed in the acronym. We can also often find Google referred from its parent company as an 'A' from Alphabet Inc..

reliance on the cloud service providers own API's for service development, fully integrating persistence, computing and networking in an inherent way, coupling them with the complementary benefits of replication, reliability, globalization and other management support procedures. This allows network function owners to devote more time to business/customers, and less time to problem solving and platform up keeping. Finally, network functions can be designed following cloud-native software development patterns, allowing for increased system openness, reducing maintenance and increasing overall coexistence of the technological arena.

This is well reflected on the recent 3GPP and ETSI standardization activities as well. The proposed Service Based Architecture (SBA) in Release-15 (Rel-15) and the enhancement on Service Based Architecture (eSBA) in Rel-16 (which extends the service concept from the 5G core control plane to the user plane functions) are two good examples of this action. Taking the cue from 3GPP, ETSI has published NFV referenced architecture to adapt for the Cloud Native and enhancement to NFV framework to include Containers as part of the reference architecture.

3.4.3 Far and deep edge integration

The deployment of edge networks has evolved from a single defined location (i.e., anywhere except in the datacenter), into a 'divide-and-conquer' approach where different degrees of edge (i.e., its distance from the datacenter versus closeness to the end user devices) could be used as the deployment base for functions and services. Especially when mobile communication networks serve more and more industry scenarios, the innovations at local communication becomes more important. The main focus at the edge of the network explores the network performance limits (especially the wireless part) and network isolation so that industry customers can use the connectivity service based on cost-efficient logical industry network. Requirements, such as latency, dictated the optimal positioning, which would be balanced according to deployment complexity, cost or scale. Under this respect, the notions of near-edge, far-edge and deep-edge surfaced, here expressed according to their distance from the datacenter.

However, high amount of relatively independent and isolated wireless logical dedicated networks cannot leverage the power of digital transformation platform at larger scale, which may even become the impediment of further industry innovation. Hence, this future architecture revolution needs continue and may highlight the deep and seamless convergence of communication and computing in order to enable the vision to establish ultra-high performance and unified data provisioning platform. Moreover, the deployment considerations involved in differentiating these sub-edge utilizations have created a domain segmentation and isolation that impacted the provisioning of key mechanisms in the edge, namely security. Despite the individual requirements and operational constraints of each segment, the application of automation and softwarization mechanisms stemming from cloud innovations will provide the necessary interfaces to allow the deployment of services in a holistic, optimized way.

3.4.4 Open ecosystem

Openness is a key driver for ecosystem innovation, as illustrated in previous generations of cellular networks. In 4G, it paved the way for new applications and Internet services. In 5G, the degree of openness was even larger, deriving in new applications, new services and industries (like automotive, Industry4.0, automation), and new business opportunities. A key point for the creation of an open ecosystem is the coordination among various leading groups, such as standardization bodies, open source projects, alliances, partnerships, and variety of industries. They are coordinated to provide supply chain diversity, solution flexibility, and new capabilities that lead to further competition and innovation.

The key elements for open radio access and core networks are: cloudification and virtualization, intelligence and automation, and open interfaces for both the radio access network and the core network. In future open ecosystem, it is needed to empower cloudification and virtualization of networks, to bring efficient management and automation to the next level. This started in 5G, in which, thanks to the cloudification and virtualization, operators and service providers had the opportunity to sell slices to different vertical industries. This paradigm shift in 5G has created a trend to leverage the existing infrastructure and optimize the available resources as much as possible, evolving towards an orchestrated and virtualized network. In this context, service federation and resource federation are considered for a further evolution [3.30]. Thanks to the introduction of open ecosystem, the model of owning and controlling the end-to-end network infrastructure is getting obsolete. Even though, further evolution is foreseen for 6G with two key ingredients: programmability in software and open-source block chain standards. Programmability in open software is offering the opportunity to avoid that nobody can take unilateral control over the system, thus pushing for further innovation. For that, a set of protocols that are open and networks that are neutral are needed. Still, how to guarantee trust in such open ecosystem is an issue. To guarantee trust, we need to decentralize the system management, as Bitcoin did with decentralized and collectively-owned data bases [3.31]. So, blockchain solutions will be the key to program and guarantee trust in the future.

4 EVOLUTION OF TECHNOLOGY ENABLERS & USE CASES

6G will take a forward-thinking approach and permits the involved entities to freely think about whatever possible from their perspective on 2030 and beyond. In a high-level perspective, without going into the technical details, players are working on a futuristic vision that allows the interaction between virtual, physical and digital worlds [3.25]. Probably two important quotes on this approach are:

a) *'Taken together, the elements of 6G will form one seamless system, having all the needed capabilities and empowering the vision of ever-present intelligent communication. With a foundation of trustworthy systems and a highly efficient compute fabric with built-in cognition capacities, the networks of the future will deliver limitless connectivity for upcoming applications and services. This will make 6G a broad platform for innovation and the information backbone of the society'*

b) *'we'll see a confluence of the digital, physical and biological worlds with human beings at the center. We will see the rise of the augmented human. Physical and cognitive augmentations will make humans endlessly more efficient and productive. The biology of humans will be mapped accurately at every instant and integrated into the digital and virtual worlds'*

It could be envisaged that 6G will continue to transform from connected people and connected things, to connected intelligence [4.1].

4.1 INTEGRATED SENSING AND COMMUNICATION (ISAC)

The mobile network will connect a large number of intelligent devices in a smart fashion. These intelligent nodes will have the capability to sense their surroundings, and exchange their observations through communication. In addition, AI can be combined with sensing capability, for the nodes to fuse the physical and biological worlds with cyber worlds such that the network will have human like cognition capabilities.

Sensing has all along been a standalone function and is often supported by a separate system such as radar, lidar, or the professional CT and MRI. In the current mobile communication network, the only capability of sensing is the positioning of the mobile devices with the help of signalling and measurement from the device. In the future 6G communication system, due to the use of higher frequency bands (mmWave and THz), wider bandwidths, denser deployment of large antenna arrays, sensing will become a new function integrated with the communication system to provide sensing, localization and imaging very high resolution and accuracy. These capabilities in the integrated sensing and communication (ISAC) system will in turn enable new usage scenarios in future consumer and vertical applications including environment-aware immersive human-centric communications, factories of the future (Industry 4.0), automotive and transportation, energy, healthcare/e-health and so on [4.1].

4.1.1 Concept

In the ISAC system, sensing and communication functions will mutually benefit each other within the same system. On one hand, the communication network as a whole can serve as a sensor. It can use the radio signals transmitted and received by network elements and explore the radio wave transmission, reflection, and scattering when it interacts with the objects and/or environment to sense and better understand the physical world, providing a broad range of new services, including (but not limited to) high accuracy localization, gesture capturing and activity recognition, object detection and tracking, as well as imaging and reconstruction [4.2]. On the other hand, the capabilities of high-accuracy localization, imaging, and environment reconstruction obtained from sensing assists and improves the quality-of-service and performance for communication such as more accurate beamforming, faster beam failure recovery, and less overhead to track the channel state information (CSI) [4.3-4].

Spectrum has always been a scarce resource and using it simultaneously for both sensing and communication undeniably gained in terms of efficiency and cost effectiveness as compared to dedicated spectrum usage. The integration of sensing and communication functions can happen at different levels [4.5], as illustrated in Figure 4.1.1-1, from loosely coupled to fully integrated, from shared spectrum, shared hardware, to shared signal processing and protocol stacks, and even cross-module, cross-layer information sharing, benefiting one another. With ISAC, it is easy to imagine that an autonomous driving car could work well or even better in all types of weather and light conditions without being equipped with separate and high cost sensors.

Besides the wider spectrum and the larger number of antennas, the sensing functionality and performance will be further enabled by other technology innovations such as the larger scale of cooperation between base stations and UEs, the joint design of communication and sensing waveforms, advanced techniques for interference cancellation, as well as the native AI capability to better deal with the sensed data, and to perform the non-linear and very likely non-convex optimizations in the joint design of the integrated sensing and communication system [4.6].

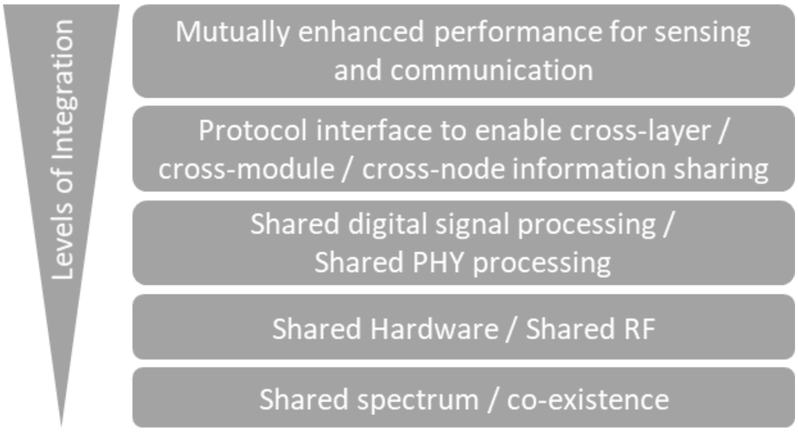

Figure 4.1.1-1 Possible levels of integration in ISAC system.

4.1.2 Use cases

The sensing use cases offered by the future 6G ISAC system include ultra-high accuracy localization and tracking, simultaneous imaging, mapping and localization, augmented human sense, gesture and activity recognition, as illustrated in Figure 4.1.2-1. We shall elaborate how these use cases would take a role in future vertical applications below.

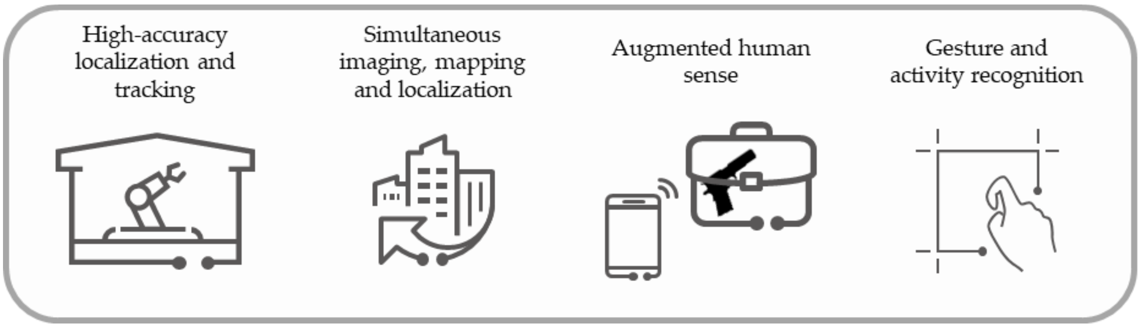

Figure 4.1.2-1 Four categories of typical ISAC use cases in 6G [4.2].

- **High-Accuracy Localization and Tracking**

In 6G ISAC system, the large bandwidth beyond mmWave bands and ultra-massive MIMO technologies can provide superior resolutions and excellent multipath resolving capabilities for high-accuracy localization applications for both device-based (e.g. UE connected in the 6G networks) and device-free (environment objects) objects. In addition, the dense deployment of massive antennas will also enable high precision direction estimation. With such sensing capabilities, the collaborative robots in future smart factories can work safely with humans and also with each other. Some examples of collaboration between moving robots may include a drone landing on a moving carrier vehicle to get charged; a delivery robot refilling liquid or solid substance to a smart container (bin/tank) when it is detected as empty, etc. In such proximity use cases, centimetre level localization accuracy is required to perform the task.

Moreover, in future smart transportation system, a user device, no matter on pedestrians, bikes, vehicles, roadside units, delivery drones, or UAV taxis, is able to precisely obtain its location information, communicate and sense its surroundings for other moving objects in the order of centimetre range resolution, sub-m/s velocity resolution and sub-degree angular resolution. In this case, the effectiveness and safety of such intelligent transport system will be greatly enhanced.

- **Simultaneous Imaging, Mapping, and Localization**

6G ISAC based sensing capabilities in simultaneous imaging, mapping, and localization enable the mutual performance improvements of these functions which opens up the realm of possibilities in 3D indoor/outdoor non-line-of-sight imaging and mapping. For instance, the sensors on single mobile vehicle usually have restricted view and limited coverage due to the weather, obstacles and sensors' power control. That said, nearby moving vehicles and stationary base stations can jointly provide a greater field of view, longer sensing distance, and higher resolution with the help of an ISAC system. Thus, the vehicles can use the reconstructed map processed by the base stations to determine their next move to achieve higher levels of autonomy. Furthermore, the sensing resolution and accuracy performance significantly improve due to the fusion of imaging results that are shared globally through the network with cloud-based services. The densely distributed base stations in the urban area and ISAC make environmental reconstruction and 3D localization possible, which in turn form the virtual urban city. Similar use cases could be applied to indoor factories with many autonomously moving AGVs or robots.

- **Augmented Human Sense**

With the use of much higher frequency bands, the ISAC system can be implemented in portable devices to augment human senses and enable people to 'see' beyond the limits of human eyes [4.7]. Such capabilities can be equipped on portable terminals (sensing devices such as 6G-enabled mobile phones, wearables or medical equipment implanted beneath the human skin). This will open the door for numerous applications, such as remote surgery, detection of slits on products, and sink leakage detection where very high range and cross-range resolutions are required.

6G ISAC capability can also play an important role in the promotion of medical technologies applied to diagnosis, monitoring, and treatments. Chronic diseases (asthma, arrhythmia, hypoglycemia, etc.) need to be constantly monitored in the long term using wearable devices. In this case, UE with ISAC capabilities can immediately help doctors in remote distance to acquire accurate information on a patient's condition such as heartbeats, and detect real-time images of the blood stream beneath the skin.

When THz band is exploited, spectrogram recognition becomes another capability that could be offered by 6G ISAC system. This includes the analysis of absorption, reflectivity, and permittivity parameters, which helps to distinguish the quality of materials. Calorie calculation, product quality management and food content identification (e.g. presence of contaminated ingredients) have been mentioned as some of the prospective food sensing applications of this technology. This property of spectrogram sensing can also be used for the non-destructive testing of industrial products such as to accurately determine the water content of wood, paper, etc.

- **Touchless Control with Precise Gesture Recognition**

Device-free gesture and activity recognition based on the joint capability of sensing and machine learning is another promising aspect of 6G ISAC applications to promote contactless user interfaces and camera-free supervision where privacy can be protected. With high classification accuracy, many functionalities such as gesture recognition, emotion recognition, heartbeat detection, fall detection, respiration detection, sneeze sensing, intrusion detection, etc.

can be implemented in a smart hospital in the foreseeable future. As a novel usage scenario, the medical rehabilitation system in the smart hospital enables automatic supervision of patients during their physiotherapy exercises. There will be automatic prompt alerts on incorrect movements or gestures, thus significantly improving the patients' rehabilitation. Moreover, the emotions of the patient could also be recognized and monitored which is important to automatically detect symptoms of depression, anxiety and bipolar disorder, allowing early response to such conditions.

To take it a step further, more complicated functionalities could be realized by the advanced hand gesture capturing and recognition system. A futuristic example would be the playing of a virtual piano in the air [4.2] through the sensing function in the 6G network, which provide a completely immersive experience anywhere, anytime. Without doubt, this futuristic concept would open up the realm of possibilities for many more innovative contactless control applications related to high-accuracy finger motion detection and tracking.

4.1.3 Challenges and future research directions

ISAC system design is in its infancy and major challenges still exist in the practical implementations of this system. In spite of that, ISAC is identified as a core technology in future communication system and significant amount of new research over the next few years will enable an optimized, native design for 6G system. Some of the major challenges and key research directions for ISAC are discussed as below.

- **Fundamental trade-offs and new evaluation metrics**: A theoretical framework [4.8] is necessary to analyse and evaluate the performance of current ISAC solutions in order to identify the benefits and any short comings, where subsequently the latter need to be addressed. The first step is to define ISAC as a general framework in which any RF signal can be used to convey both the communication data and the sensing data. Since both data are communicated using a single RF source, a fundamental trade-off seems to exist between the communication and sensing performance and therefore a unified upper bound and its achievability will help to characterize this trade-off which in turn will provide the design criteria for the ISAC network. A possible research direction is to bridge information theory with detection theory. By considering the communication performance as characterized by the achievable rate and the sensing performance as characterized by the distortion measure, it is desirable that a closed-form expression can be derived with the objective to form a connection and optimized the channel capacity (for communication) and Cramer-Rao Lower Bound (for sensing).

- **Hardware imperfections:** Current design of the ISAC system calls for the baseband and RF hardware to be functionally shared since the integrated hardware solution reduces the overall power consumption, system size, and information exchange latency between the two systems. In addition, the hardware converging strategy would facilitate the mutual aided functions of sensing and communication in distortion calibration and compensation. Considering the cost and size difference between the historical communication and radar systems, the ISAC system hardware design would be closer to the traditional communication architecture. As a trade-off, we need to consider the impact of distortion parameters on sensing performance. Proper design of integrated RF architecture with self-interference cancellation is important for ISAC system.

- **Joint waveform design and optimization:** The main challenge for the joint waveform design is the very different KPIs for communications and sensing where the communication performance objective is on maximizing the spectral efficiency, while the optimum waveform design for sensing hinge on improving targets estimation resolution and accuracy, including the MIMO and large-bandwidth friendly waveform OFDM, and the more traditional radar waveform FMCW. Current state of the art suggests that there is still room for waveform design to strike a balance between good communication and sensing performance.

- **Artificial Intelligent enabled ISAC**: AI is regarded to be an efficient method of dealing with intractable problems that we faced in ISAC. For instance, learning-based approaches could be used to improve the sensing service such as gesture recognition and imaging [4.9]. Moreover, in cooperative ISAC scenarios, node beliefs can be shared in spatial and temporal dimensions, thereby improving sensing performance through multi-node spatio-temporal cooperation. The RF sensing performance also depends on the data processing and fusion algorithms used in the state updates where the belief propagation algorithms and fusion algorithms with learning-based approaches can inherently benefit cooperative sensing and should therefore be studied. Owing to the acceleration of parallel computation, the AI schemes can operate faster and are thereby more applicable in practice in 6G.

- **Networked ISAC:** ISAC in the mobile communication network provides great opportunities and benefits for synchronized multi-static sensing. Integration of sensing capabilities into the existing communication network will be the most viable and cost-effective option where multiple network devices (base stations, UEs) can function as a multi-static radar to enable network sensing operations such as moving target detection and scene imagery. In addition, this offer interesting possibilities for being able to carry out sensing under non-line-of-sight (NLOS) conditions. The research challenges here would lie in the synchronization, joint processing and network resource allocation in order to achieve the optimum fusion sensing results.

4.2 NEW USER EQUIPMENT

It is very exciting to think about, but also difficult to anticipate what would be the new type of user equipment, which would break to the markets for 6G. However, some trends can be seen for that, for example the different types of wearable devices have become more common over the years. It could be foreseen that the trend will continue, and more intelligent and more capable connected wearable and embedded devices are entering to the markets, which could enable also deep-edge or mobile mist computing with the powerful user equipment as discussed in Section 0. Considering what the advances in technology could provide in future, that would be even smarter and smaller devices with better computing and communication capabilities. This would of course require advances in microelectronics (incl. novel efficient and secure processors and processor architectures), energy storage (battery technology) and communication technology.

For sure, new type of user equipment will be needed to enable the different foreseen use cases, which we have pointed earlier in subsection 0. It is to be seen whether we are talking about devices, which are more intelligent and capable of performing multiple tasks, or devices, which are simpler and most of the complex actions are performed in-network.

The ultra-smart wearables in personal use and also professional use, could provide more flexibility in use. For example, in professional use and challenging work conditions, using current mobile phones and tablets are challenging. So, simple, intuitive, multimodal, and easy to use interface to interact with devices, services, and surroundings, are needed. As today, the handheld smartphones are used basically to provide all the user experiences, phone functionalities and interaction with services. Tomorrow, the smartphones could be replaced by smart glasses and wearable, smart patches etc., to deliver extended reality experiences, phone functionalities and interaction with Internet services. In a way, the functionalities of current mobile phones would be distributed to other connected devices, which are more suitable for providing enhanced user experience. The use of such dedicated devices is driven by the technologies like telepresence, haptic user interactions, holographic displays and content distribution, multi-dimensional imaging, internet of everything, and extended reality applications. Of course, one could consider also the new type of morphing handheld device, which can change its appearance and function when needed. Such a device could be based on elastic microelectronics (e.g., printed electronics), flexible and morphing displays, and input devices interacting directly e.g., with wetware and biological systems.

In addition to the ultra-smart devices, the other approach would be to increase the capabilities of environment with minimal use of end-user gadgets and devices. The gadget-free vision, which has been also called as Naked World vision [4.10], emphasis the need for smart metasurfaces and network architecture, which is distributed and dynamic, similar than the 6G architecture is foreseen to be. The services can be orchestrated close to end-users and end-users are able to interact with services with minimum number of personal devices, and with more simple functionalities. If the manufacturing costs and complexity are low, material reusability high and even biodegradable materials can be used for these simple devices, it may have a positive impact on the sustainability. One possible direction in research could be also towards connected nano-things and bio-nano-things, which could interact with biological systems and act as sensors and actuators to interact with environment. That could be part of development for multimodal user interaction and human-machine interactions.

Multimodal (Hear, Visual, Taste, Smell, Touch and Emotion) user interaction communication is required by future verticals to deliver services based on user experience & terminal functionalities to allow the service providers to optimize their services and resources by connecting intelligence.

New sensory/actuator integration results in new user equipment capabilities and functionalities required by future holographic XR/multisensory XR applications, further increases the demand on processing power required to execute the computation-intensive and low-latency tasks.

4.2.1Concept

Contemporary wireless user equipment (UE) design becomes more challenging and complicated than ever. In any mainstream user equipment, it does not only need to co-exist with several prevailing wireless technologies, but also integrate new sensory/actuators (including camera(s), audio, display, fingerprint scanner, vibrator, gyroscope), as well as improving battery and wireless charging. Soon, there will be a stronger need to enable or enhance various functions and technologies, such as virtual reality, augmented reality, internet of senses, all of which further increases the difficulty level of UE design including battery, processors, memories, analogue, circuit & system, antenna, and system design [4.11]. New applications can be delivered over multiple terminals belonging to the same user overcoming limited computing resources and the latency requirements of future vertical applications such as tactile internet (TI) [4.12] use cases.

New UE types could be classified and used by health, entertainment or industry verticals as following:

- **Implantable:** Implantable miniature sensors and 'nanosensors' devices include cardiac pacemakers, implantable cardiac defibrillators (ICDs), coronary stents, hip implants, interocular lenses and implantable insulin pumps. Some implantable medical devices, such as a pacemaker, may be battery-powered. Also, Biomolecular Sensing devices (DNA microarrays, Chemical sensors). Example use cases could be for instance, people may have devices on or beneath their skin that monitor heart rate, glucose, or oxygen saturation and help control chronic conditions like diabetes or respiratory disease. The monitoring could enable people to live at home instead of having to move into an assisted living facility.
- **Wearable:** Sensors that are embedded in some type of garments/textile to monitor (ECG, EEG, EMG, EOG, accelerometers, BVP, glucose sensors, GSR, PPG). Example use cases could be for instance, paramedics and firefighters may eventually be required to use wearables that track their heart rates, emotion and stress levels.
- **Tattooable:** Ultra-thin electric mesh for human skin, or temporary skin that can store data and deliver drugs—and electronic second skins made of microscopic semiconductors [4.13]
- **Smartphone/portable terminals (VR/AR/ER):** Sensors embedded in the user's devices. For instance, doctors, too, may regularly use smart glasses to review a patient's anatomy in 3D before surgery.
- **Ambient Sensors:** Sensors monitoring user's activities (e.g., PIR, RF imaging, surveillance cameras - fixed or on drones)
- **Actuators:** Haptic devices to provide feedback for navigation or alarm (haptic buzz), display interface (braille language), interaction (haptic gloves/belt/suits), remote industrial control (robot arms with a number DoF, haptic signal amplitude range, temporal and spatial resolution).

4.2.2 Use cases

- **Biometrics to enhance security**

New user equipment capabilities on collecting biometric data collection can advance security solutions (such as authentication). While existing authentication mechanisms relay on SIM (subscriber identity module or subscriber identification module) cards in mobile devices, unique biometrics collected from the users can be used to enhance the security. Considering a scenario where the SIM card token is stolen, an alternative/complementary method of ensuring network connectivity for the genuine user would involve the use of biometrics as these cannot easily be stolen. Biometrics offers a solution to the weaknesses of knowledge and token-based systems. Examples of continuous biometrics are face, iris, keystroke dynamics, touchscreen gestures, behavioural profiling (e.g.: Bluetooth/Wi-Fi/GPS), gait, mood and one-shot biometrics are face, iris, and fingerprint that can be collected by the new user equipment discussed in this subsection.

- **Distributed new user equipment to enhance localisation**

Existing localisation techniques typically consider a single user equipment for localisation. The impact of the user equipment distribution to process and present multimodal services can also be used for improved accuracy of positioning using several equipment positioning data for localisation.

- **Continuous biometric monitoring to enhance user experience**

Predicting and optimising the position of edge application/network function positions and/or slice make-up can enhance service providers to operator to optimize their resources based on user equipment biometric collection when users are reacting to network performance. Dynamic edge/slice relocation during a session based on continuous biometric collected by new user equipment can advance and predict user haptic experience. For instance, during a telepresence of a family meeting, haptic feedback may be used to communication emotion e.g., hug/handshake at the start and end and so the higher cost slice/edge requirements are not needed for the whole session.

- **Computing (Distributed device-to-device, device-to-edge, device-to-cloud)**

Offloading computation-intensive tasks from such resource scarce devices to be executed across distributed resources over various networks, towards minimising the response time and power consumption has recently gained popularity and has been identified as a crucial technique for improving multimodal applications. For instance, edge/cloud rendering, network transmission and VR device local rendering and display where VR display can be divided into several segments on the device-to-device scenario. Another example for device-to-edge offloading is to consider requirements, such as latency, to locate the processing to an optimal positioning on the edge.

- **User feedback/control (robots' arms, haptic glove/suit, drones)**

Various sensors, actuators, display devices are used to provide a realistic haptic & multimodal interaction with the remote devices over a uni-directional or bi-directional communication. The sensor components capture the tele-manipulation instructions (e.g., kinaesthetic) in the master domain, and the resulting changes in the control domain (e.g., haptic feedback). Actuators, in both local master and remote-control domains, execute the user's tele-manipulation instructions. The number of independent coordinates used for providing the end user experience at the master domain (using Human System Interfaces), and for controlling the velocity, position, and the orientation of the controlled devices is defined by their DoF.

4.2.3 Challenges

- **Offloading response time**

Offloading algorithms must aim for minimising the total time spent on offloading. Moreover, improved resource allocation and management of resources at each constituent resource providers (e.g., Radio, Non-Radio, and Computing) in the end-to-end system is paramount to reducing the total response time when offloading.

- **Multimodal Synchronisation**

The incorporation of various human-system interfaces in tactile Internet (TI) with specific hardware functionalities and the distributed execution of functions are key aspects of terminal evolution in TI. The dynamic inter-connection of these distributed functions and tactile devices (TDs) can be seen as the composition of various hardware and software functionalities towards providing/improving the user's experience. The haptic and bidirectional communication brings consumption of experiences closer to humans (as opposed to experiences that are consumed today through mobile devices, for example). This increasingly distributed and human-centric experiences that are enabled by TI require new and improved means for gathering and enforcing quality of service (QoS) and quality of experience (QoE) metrics. Such requirements must be enforced throughout the distributed system, for improving not only the latency and reliability, but also the user's haptic, visual, and audio experiences. However, for ensuring requirements in more dynamic scenarios where systems must adapt to satisfy/maintain requirements, dynamic methods for capturing both objective and subjective metrics of user experiences must be provided.

- **Multi-Modal Parallel Transmission**

The end-to-end communication between the new user equipment includes several modes of communication at the same time (e.g., video, audio and haptic) [4.14]. This results in generation of multiple streams in parallel which ultimately need to be presented to an end user in harmony. Otherwise, the QoE of the user may not be satisfactory due to lack of precise synchronisation across these parallel streams. For example, one stream may get delayed while others are delivered on time. Apart from the synchronization challenges, the instability of the underlying network condition of a stream may also impact the performance of the other parallel streams of the same TI application. These mechanisms can significantly benefit when there is an explicit feedback mechanism between TI applications and networks.

4.3 INTEGRATED TERRESTRIAL AND NON-TERRESTRIAL NETWORK

As defined by 3GPP [4.15], a non-terrestrial network refers to a network, or segment of networks using RF resources on board satellites at different orbital positions or Unmanned Aerial Systems (UAS) platform. A satellite (or UAS platform) which may implement either as a relay node or base station, thus distinguishing transparent and regenerative architectures. Herein, we consider an NTN in a broader sense. It may include maritime networks formed by floating devices (e.g., autonomous ships) as well as underwater networks increasingly relevant to explore and monitor the ocean with autonomous surface vehicles (ASVs) and autonomous underwater vehicles (AUVs).

4.3.1Concept

NTN plays a role to expand the service coverage of terrestrial networks and provide continuous connections for areas not covered by terrestrial networks. Due to the extensive service coverage capabilities of space/aircraft vehicles and reduced vulnerability to natural disasters, non-terrestrial networks are expected to integrate with terrestrial networks to form a global 3D integrated communication network covering the earth, including the sea, land, air, and sky. Integrated non-terrestrial and terrestrial communication system will bring new functions to users. Using the 3D coverage of the integrated system, not only communications with broadband and wide range IoT can be realized around the world, other new functions such as enhanced positioning and navigation, real time earth observation can be integrated into 6G system. The market already expresses interest in how private networked satellite system can enable distribution, processing, and execution of tasks; and the gathering and distribution of data from the very edges of the world and back again while achieving quality of service suitable for their operational requirements.

The integrated network should meet various service requirements of users everywhere, which is an important direction for future communication system development. The convergence of non-terrestrial and terrestrial network will give full play to their respective advantages to provide users with more comprehensive and high-quality services. The integrated network will provide continuous services. No matter on foot or vehicle, or on board an aircraft, even when some infrastructure is damaged due to disasters, the terminals will be able to support non-terrestrial and terrestrial networks and the service continuity will be ensured.

4.3.2 Use cases

- **Extreme coverage**

A recent 2022 study by the ITU found that 2.9 billion people are without internet access worldwide, with a majority of them located in rural and remote areas and in developing countries [4.16]. Deployment of NTN will be helpful in addressing this important challenge that by providing affordable and reliable connections and broadband services. Using a satellite relay

Aerial platforms such as drones, balloons, and High Altitude Platforms (HAPS) will be major enablers within the context of next generation networks [4.17]. Due to their controlled, dynamic positioning, they will enable the deployment of wireless coverage and capacity on-demand, in a very flexible and controlled way, with a strong Line-of-Sight (LoS) communications component; in particular, this will favour ultra-high bandwidth Terahertz, visible light, and wireless optical communications. These aerial platforms may be used for creating on-demand wireless access networks, on-demand backhaul wireless networks, or both. The dynamic positioning of the aerial platforms will bring up an additional degree of freedom when compared to what is possible with the virtualization available in 5G and make the deployment of wireless networks even more agile.

- **Mobile broadband for the unconnected**

The current commercial satellite communication system has very low transmission rate and high cost for User Equipment (UE) and services. In the future, integrated non-terrestrial networks and terrestrial networks will offer common radio access technology-based end user terminals, with substantially lower costs. The solution will support also network and service integration to support seamless handover and continuity of services.

Furthermore, satellite communications will complement terrestrial networks, with the full integration of satellite and cellular communication opening a new chapter in wireless communications in the 6G era.They are envisioned to be suitable to serve remote areas such as the oceans and rural areas, where terrestrial-like networks are harder or non-cost-effective to be deployed. The predictability of the movement of the satellites around the globe will enable the design of new NTN-related solutions and mechanisms, including intra-NTN routing and truly seamless handovers.

- **Broadband connection on the move**

The transportation platforms on the move include aircraft, train, car, ship and so on. Take the aircraft scenario for example, in 2019 over 4 billion passengers travelled with aircrafts, most of them have no internet connection during the flight or very low speed internet access. Future communication systems should provide MBB experience connection for all the aircraft passengers.

- **First responder communication and disaster relief**

Terrestrial infrastructure is vulnerable to natural disasters, such as earthquakes and tsunamis. A continuous and reliable emergency communication system is necessary in disaster scenarios to provide disaster prediction, warning, emergency response, and emergency communication. Emergency communication provides users with services to handle emergencies and natural disasters in a timely manner. Non-terrestrial network and terrestrial network can be used to support the management of public emergencies and support network and service integration to support seamless handover and continuity of mission-critical voice, broadband data and video services for first responders across the globe.

- **Wide-ranging IoT services extended to unconnected locations**

Already satellite sensor networks cover e.g., maritime safety, sustainable management of marine resources, wild-life and environmental monitoring, albeit with relatively low data rates. In future unmanned operations over e.g., oceans, land masses without reach of terrestrial networks, high data rate upload and collection is required, i.e., smart and uncrewed ships, cargo monitoring, shipping and so on. In future, an IoT device should be able to connect and report information at anywhere by anytime. Therefore, in remote areas and uninhabited areas, it will be more convenient to collect various information through NTN. The integration of underwater and maritime networks in the NTN concept will be a major step to cover this new relevant environment for the economy and regarding climate change issues.

- **High precision positioning and navigation**

In the future, the navigation precision provided by Global Navigation Satellite System (GNSS) is not enough for future vehicle auto navigation services. The integrated network can provide high-precision navigation services in remote areas or unmanned areas by combining GNSS services and LEO satellite constellations. The positioning precision can be improved from 10 meters to 10 cm. Based on this, automatic driving navigation, precise agricultural navigation, mechanical construction navigation, and high-precision user location services can be provided.

- **Real-time earth observation and protection**

Earth observation is the gathering of information about the physical, chemical, and biological systems of the planet via earth observation technologies. The future earth observation will realize real-time and high resolution ultimately and can be introduced to more scenarios in the future, such as real-time traffic dispatch, real-time 3D maps open to individual users, high-precision navigation combining with high resolution remote imaging and positioning, quick response to disasters and so on, either on land or at sea.

4.3.3 Challenges and future research directions

- **Air interface & Spectrum efficiency**

Due to the high-speed mobility, wide coverage and long transmission distance of non-terrestrial nodes, the air interface transmission technology of terrestrial networks cannot be directly applied to non-terrestrial networks and needs to be improved and optimized. New air interface technologies need to improve the anti-Doppler frequency offset capability, long-delay access capability, and enhance the UE access and hand over mechanism in a large coverage area.

The overall spectrum efficiency of existing non-terrestrial networks is much lower than that of terrestrial networks, partly due to limited power of non-terrestrial nodes and low link budgets due to long transmission distances, and partly due to interference between non-terrestrial networks and between non-terrestrial networks and terrestrial networks.

For future 3D space networks, new optimised interface and anti-interference technologies need to be introduced to improve the spectral efficiency of non-terrestrial networks.

- **Dynamic routing**

Routing is one of the key technologies for non-terrestrial network. Different from the terrestrial network, the satellites, HAPS and UAVs are moving fast and the connections between those space-based nodes are broken and reconstructed frequently, which makes the network topology change constantly. Routing protocols oriented to the terrestrial Internet, such as RIP and OSPF, are difficult to adapt to high-speed non-terrestrial networks. Different from the terrestrial network nodes, the movement of satellites in non-terrestrial network is regular, which provides a feasible way for the routing design of satellite network by making full use of the regularity. According to the characteristics of satellite networks, new dynamic routing technologies can be developed, such as time virtualization routing technology, location virtualization routing technology, etc. Also, given the possibility to control the position of HAPS and UAVs, new dynamic routing approaches can be developed, taking advantage of the inherent control of the network topology.

- **Integrated network architectures**

In the 3GPP NTN architecture, the gNB and gNB-DU are extended to non-terrestrial networks to construct a satellite-ground converged network architecture. Based on the concept of extending base stations to non-terrestrial networks, the typical integrated network architecture explores the solution of separating core network functions and deploying some of the core network functions on non-terrestrial networks. Furthermore, the integration of the non-terrestrial networks and terrestrial networks requires a more comprehensive network architecture design. The integrated network is not a simple interconnection between satellites, HAPS, UAVs and terrestrial networks, but a deep integration of space-based, and ground-based networks in terms of system level. The integrated network will consist of unified terminals and unified air interface protocols. The access network and core network should be integrated to construct a unified control plane and data plane.

- **Open issues**

Although the integration of NTN and terrestrial networks can bring many new application scenarios, and bridge the digital divide, there are still many challenges and open issues that need to be considered and solved, such as:

1) Spectrum sharing and frequency coordination in multi-layered NTN networks and between non-terrestrial networks and terrestrial networks,
2) Inter-satellite links technologies,
3) On board edge computing, SDN and virtualisation technologies,
4) Federated 3D NTN-TN network control, management, and resources management,
5) Unified NTN-TN services models,
6) Unified security solutions for NTN-TN networks,
7) Overall cost and energy optimisation of integrated NTN-TN networks.

4.4 THz WIRELESS SYSTEMS

4.4.1 Concept

The deployment of THz wireless systems with 10 Gbps data rate will be the key for 6G. The critical passage from the laboratory to production for wide scale deployment will be fostered by further research and industry investments. The Horizon 2020 programme funded a high number of projects to develop multi-Gbps technology, creating a portfolio of opportunities that has to be converted in real product. A step change in the design, production and economy of THz component is needed. This process has to be led by industry with investment and creation of skilled workforce.

The integration and reliability have to be ensured by co-design of system and component with high integration level and advance manufacturing methodologies.

Finally, the economy of millimetre wave and high spectrum band technology is quite promising with a market estimated of about 2.2 trillion dollars by 2030, including the 28 GHz range.

4.4.2 Use cases

As discussed earlier in subsection 0, ultra-wide bandwidth, microsecond latency, and seamless data transmission are the typical features of THz technology, which is expected to change the route of the mobile communication landscape in the era of 6G. By using the frequency range over 100 GHz, the potential ultra-wide bandwidth and 100 Gbps data rate for mobile communications will eventually be enabled. With such features of THz communications, rail transport is anticipated to step into a new era of ‘smart rail mobility’, where trains, passengers, infrastructure, and goods will be thoroughly interconnected. The train-specific service requirements for 5G are handled in technical report (TR) 22.289 ‘Study on Future Railway Mobile Communication System’ as a part of 3GPP SA1. 5G-enabled wireless connection with train ecosystem will be interworking with GSM-R, where the use cases are mainly along access to the system, uncontrolled power down, assured voice communication (AVC) for shunting operation, role management and presence. For ‘smart rail mobility’, as shown in Figure 4.4.2-1, the high-data-rate transmission will be realized in five refined scenarios: train-to-infrastructure (T2I), inside station, train-to-train (T2T), infrastructure-to-infrastructure (I2I), and intra-wagon. The relevant applications will support not only the critical signals for rail control and dispatch, but also various potential high-data-rate applications: on-board and wayside high-definition (HD) video surveillance, on-board real-time high data rate connectivity, train operation information, real-time train dispatching HD video, and multimedia journey information. Considering using several tens of MHz bandwidth to support compressed HD video and assuming about 100 passengers or user devices of a wagon, a total bandwidth of several GHz will be required. Thus, only in THz band, the large frequency spectrum is available.

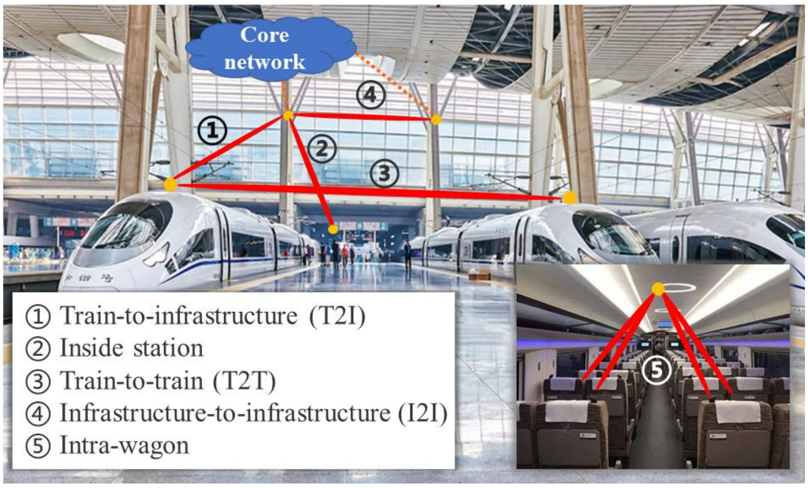

Figure 4.4.2-1 The view of five 'smart rail mobility' scenarios

Among these refined scenarios, one big challenge appears in the T2I scenario. The wireless link should guarantee close to 100% availability as well as very low latency when the train is traveling at a speed of over 350 km/h. This link, as the main interface between the onboard network and fixed base station, will form the aggregated stream for the backhaul of T2T and intra-wagon scenarios as well. To this end, a bandwidth of dozens of GHz is required to supply up to hundreds of Gbps data rates. Such high data rate and huge bandwidth requirements form a strong driving force to exploit the THz band, i.e., beyond 300 GHz, where the available spectrum is massively abundant. Another challenge appears in the T2T scenario, because the transmission distance for ultra-high-speed communication is very limited due to very high path loss. Besides, the spectral windows in the THz band are highly distance-dependent. Hence, multi-band system, in which THz, mmWave, sub-6 GHz will jointly work, needs to be investigated thoroughly and incorporated in the performance evaluation [4.18]. With the microsecond latency, the Europe train control system (ETCS) level-3, where trains are allowed to communicate with train control centre (TCC) directly with reliable radio communications, will be realized.

In order to adequately support the design of THz system-enabled smart rail mobility, for the first time in [4.19] measured the T2I inside-station channel and intra-wagon channel at 300 GHz, respectively, to obtain the fundamental knowledge of the propagation channel characteristics. The measurement campaigns were conducted in a train test centre, using a pseudorandom M-sequence correlation-based ultra-wideband (UWB) channel sounder. In the measurements, the channel impulse responses (CIRs) at 300-308 GHz were measured. The key channel characteristic -- Rician K-factors for T2I and intra-wagon scenarios are 3.52-3.60 dB and 8.39 dB, respectively. The measured root-mean-square (RMS) delay spreads for these two scenarios are 8.92-9.23 ns and 11.74 ns, respectively. The values of Rician K-factor are larger than the similar open train station scenario at 930 MHz [4.20], while the values of RMS delay spread are smaller than the measured results in a railway depot at 60 GHz [4.21]. It implies the fact that the multipaths in THz channel are sparser than lower-frequency channels.

4.4.3 Challenges

However, due to the limitation of the two-dimensional channel-sounding measurement data for THz channel modelling, the three-dimensional ray-tracing (RT) simulator can be utilized as a major candidate to extend the channel data. An open high-performance computing (HPC) and cloud-based RT called CloudRT is recommended[8]. With the aid of RT, the THz channel characteristics of T2I and intra-wagon scenarios can be fully represented. Compared with lower-frequency channels, it is interesting to find that the non-ling-of-sight (NLOS) can be classified as light NLOS (L-NLOS) and deep NLOS (D-NLOS) according to the existence of the first-order reflection. Since the first-order reflection has a great impact on the channel characteristics as well, the new classification can be distinguished from the real dark NLOS link, providing a more precise baseline for THz channel modelling and system evaluation.

To summarize, taking advantage of ultra-wide bandwidths beyond dozens of GHz available in THz frequency range, beyond 100 Gbps high-data-rate transmission is possible to achieve. However, the challenges are obvious to realize THz technology in the era of 6G. The beamwidth of the antenna is much narrow (even 1 degree) in order to compensate for the high path loss. Thus, it is much challenging to realize adaptive beamforming in the mobile T2I and T2T scenarios. For intra-wagon and I2I scenarios, the challenge is to overcome the loss from aerodynamics-induced beam misalignment, where efficient beam alignment techniques, such as angle of arrival estimation algorithms, are still necessary to develop. According to the progress on THz standardization, the full version of smart rail mobility enabled by THz communications is expected to be realized in the era of 6G in the future.

4.5 HOLOGRAPHIC RADIO

4.5.1 Concept

Holographic radio is a new technology to create a spatially continuous electromagnetic aperture to enable holographic imaging, ultra-high density, and pixelated ultra-high resolution spatial multiplexing [4.22]. Generally, holographic radio uses the interference principle of electromagnetic waves to record the electromagnetic field in space. With the strictly coherent reference wave, the high-resolution holographic electromagnetic field can be recorded accurately if the holographic sensor is capable of recording the continuous wave-front phase of the single wave (the multipath components in realistic environments). Thus, holographic radio changes the mechanism of distinguishing two users in space from the time delay domain (reciprocal of bandwidth) to the interference domain of electromagnetic waves (half-wavelength). This means, two users close to each other with half-wavelength can be distinguished even without the need for a large bandwidth, such as millimetre-wave or THz communications. Also, due to the interference principle of electromagnetic waves, ultra-high resolution spatial multiplexing can be achieved through holographic spatial wave field synthesis technology to meet the needs of ultra-high spectrum efficiency, ultra-high flow density, and ultra-high capacity.

In order to record the holography, an ultra-broadband tightly coupled antenna array based on a current sheet follows a smart method. This antenna array does not need an ultra-dense radio frequency feed network, which can be achieved with clear implementation advantages. Different from massive MIMO dominated in 5G, holographic radio has more spatial dimensions by making good use of a diffraction model based on Huygens's principle. In addition, holographic radios can achieve high coherence and high parallelism of signals by coherent

[8] CloudRT is jointly developed by Beijing Jiaotong University and Technische Universität Braunschweig. More information on CloudRT can be found in tutorial http://www.raytracer.cloud/.

optical up-conversion of the microwave photonic antenna array. Furthermore, the ultra-high coherence and high parallelism also facilitate the signal to be processed directly in the optical domain.

4.5.2 Use cases

The main application scenarios of holographic radio include ultra-high capacity and ultra-low latency wireless access, ultra-high density wireless industrial buses in a smart factory environment, high-precise positioning, and data transmission for massive internet-of-things (IoT) devices. In addition, holographic radio can accurately perceive complex electromagnetic environments, such as smart cities, smart factories, smart train stations, etc., through the integration of imaging, perception, and wireless communications.

4.5.3 Challenges

Although holographic radio has been researched partly in the field of frequency holographic imaging and perception, its applications are still facing many challenges and difficulties. Since there are no existing channel models for holographic radios, it is necessary to converge the communication and electromagnetic theories for holographic radios. Research challenges related to the hardware and physical layer design need to be studied, including the mapping from radio frequency holography to optical holography, integration between photonics based continuous-aperture active antennas, and high-performance optical computing.

4.6 Digital Twin

4.6.1 Concept

Digital twins have become widely spread to converge physical and virtual worlds, namely in industry. Digital twin is a digital replica of the physical system that can be modelled and simulated in an offline and online mode. Digital twins are typically built based on massive information from models, sensors and operational data allowing the creation of digital replicas of the physical system. The creation of these digital twins typically implies the exchange of large amounts of data between the physical and digital twins, and brings up new communications requirements in terms of capacity and latency. Although this perspective is very relevant within the context of next generation networks, we believe the creation of digital twins of the wireless networks themselves will be relevant as well, in the era of machine learning as an enabler for creating smart networks. The creation of these digital twins will be crucial to train machine learning models in the same exact conditions they will operate in. In particular, this will consist of capturing the physical characteristics of the environment where the real network is or will be operating in, enabling for example the creation of custom-tailored propagation loss models that capture the exact propagation characteristics associated to the physical twin (in this case the real network). This will be even more crucial with the migration to Terahertz-based communications and the ability to combine sensing and communications in the network infrastructure.

4.6.2 Use cases

This effort has been already started in many vertical sectors (e.g. industry, logistic, health, etc.). On the industrial vertical, different aspects are discussed and a model proposed for creating structured descriptions of an entire 5G network, including 5G UEs are proposed based on 5G Asset Administration Shell (AAS). It includes 5G UE AAS and 5G network AAS.

- 5G UE AAS: it describes the endpoint of the 5G link at the device end, which is the 5G UE, and considers its functionalities, capabilities, and performance as defined by 3GPP.
- 5G network AAS: it is the enabling networking function, which includes all nodes and functions in the 5G RAN and core network. This 5G NW AAS includes structured

information on the following: a) 5G link network endpoint. This describes the logical function of the endpoint of a 5G link on the network side; b) 5G link. this subsection of the 5G network AAS describes the characteristics of communication between two endpoints.

Additionally, the flexibility and dynamics provided by software and virtualization-backed network operations under the scope of I4.0 have attracted the attention of sectors with unique demands, such as the ones where hard real-time communications are needed. Under this setting, the regular virtualization infrastructure management mechanisms supporting cloud-native capable network control and management impose considerable constrains. Examples of such challenges are cold start overheads that contribute to service latency, as well as unoptimized scheduling and communication mechanisms that lack suitable resource management schemes, preventing deterministic application execution and networking support. Therefore, in order to support industrial applications with hard real-time communications requirements, while bringing the advantages of cloud-based deployment, require intrinsic deterministic support in the way such systems are architected and operate.

5 CONCLUSION

This White Paper provides a holistic view on emerging and future communication, networking and other related technologies which are expected to play a key role in accelerating future digital transformation of the vertical ecosystem in the 6G era. 6G enabling technologies should enable the evolution of current vertical use cases in 5G, as well as new use cases and for existing and new verticals. It also should support vertical sectors in tackling global grand challenges such as climate change, aging population, mobility, environmental management, resource sufficiency, and digitalization of industry and citizen services. Furthermore, starting with 5G, the communication networks are the key enablers for bringing together the benefits of artificial intelligence, big data and high-performance computing to verticals. Trusted and secure connectivity and communications have also a central role in enabling cybersecurity for critical services and infrastructures of society and industrial use cases.

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Glossary and acronyms

3GPP	3rd Generation Partnership Project
5G	Fifth Generation Mobile Communication System
5G PPP	5G Public Private Partnership
6G-IA	6G Smart Networks and Services Industry Association
AI/ML	Artificial Intelligent / Machine Learning
ASV	Autonomous Surface Vehicles
AUV	Autonomous Underwater Vehicles
B5G	Beyond 5G
CDN	Content Delivery Networks
CSI	Channel State Information
DLT	Distributed Ledger Technologies
DoF	Degree of Freedom
EC	European Commission
ETSI	European Telecommunications Standards Institute
HAP	High Altitude Platforms
IEEE	Institute for Electrical and Electronic Engineering
IETF	Internet Engineering Task Force
IMDA	Info-Communications Media Development Authority
IoT	Internet of Things
ISAC	Integrated Sensing and Communication
LOS	Line-Of-Sight
MEC	Mbile edge computing
MNOs	Mobile network operators
mMTC	Massive Machine Type Communication
MIMO	Multiple Input and Multiple Output
NLOS	Non-Line of Sight
NPN	Non-public networks
NTN	Non-terrestrial network
OTT	Over The Top
PN	Public Network
QoE	Quality of Experience

QoS	Quality of Service
RIS	Reconfigurable Intelligent Surfaces
SNS	Smart Networks and Services
SDG	Sustainable development goals
TD	Tactile Device
TI	Tactile Internet
TSN	Time Sensitive Networking
UAS	Unmanned Aerial Systems
UN	United Nations
UE	User Equipment
V2X	Vehicle_to_Eeverything
XR	Extended Reality

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