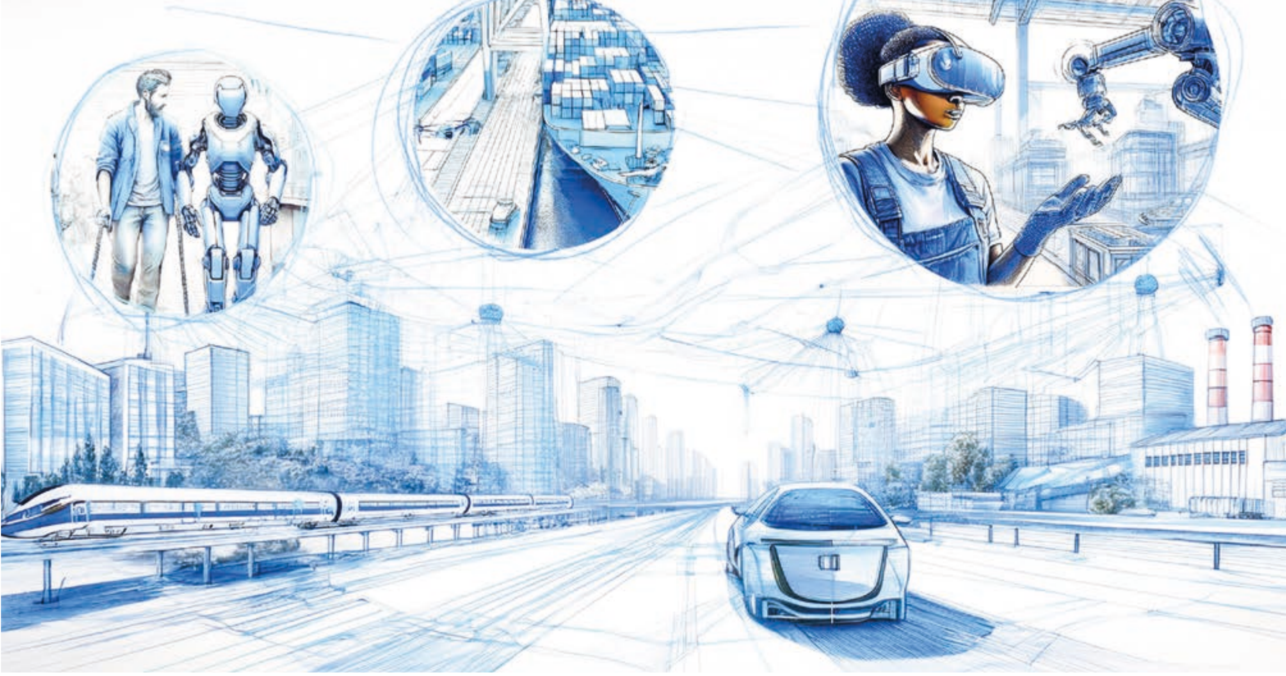

FAU Studien aus der Elektrotechnik 28

German Perspective on 6G – Use Cases, Technical Building Blocks and Requirements

Insights by the 6G Platform Germany

White Paper

FAU University Press

Norman Franchi, Falko Dressler (Eds.)

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Preface

The working group "WG:Roadmap" of the 6G Platform Germany, funded by the German Ministry for Education and Research (BMBF), has set itself the goal of identifying emerging application scenarios, new technologies, and future requirements that shape the 6G research, development, and standardization efforts in Germany and Europe. Toward this goal, the WG has collected, analyzed, and harmonized numerous 6G use cases from various academic institutions and companies under the 6G Platform. As a result, this white paper conveys the current findings from the Working Group. It presents the most recent view on the identified 6G use cases and use case families, existing and novel technology building blocks needed to realize those use cases, as well as new requirements they entail. Representing the German 6G program, the use cases presented in this white paper give insights from German industrial companies, network operators, and further communications stakeholders whose needs may differ from countries with other economic priorities. Besides, the view shown in this paper follows the alignment with the prominent European 6G projects such as 6G-SNS and 6G-IA, which is in line with the working group's goal to give a first glimpse of a German-European 6G vision.

In addition to the goal of raising awareness in the ecosystem, the white paper is primarily aimed at companies involved in 6G standardization that want to contribute to the 6G standardization process or consider new business opportunities related to 6G. That is, they can explore the use cases, technology building blocks, and requirements obtained from a significant variety of network providers, industry, and academic partners in the 6G Platform that embraces 33 German 6G projects with a total funding of 700 million Euros. Subsequently, the findings in the white paper are also relevant to industry and academic alliances and associations. Not least, political representatives and ministries supporting research and industry can use the insights shown here and map them to their envisaged scenarios.

Since this paper originates from a collection of specific and tangible use cases, which keep an application and, thus, the user in mind, the findings presented here can also serve as a basis for scientific communication purposes aiming to give an intuitive understanding of 6G.

Executive Summary

This white paper explores the transformative potential of 6G through an extensive set of use cases contributed by industry and academic partners involved in 6G Platform Germany. These use cases illustrate how 6G can drive advancements not only as a new technology but as a comprehensive ecosystem, including several applications originally envisioned for 5G but still not fully realized.

Initially, we established a framework for understanding the diverse needs and possibilities that 6G networks can address by systematically collecting and clustering the use cases into eight use case families (UCFs). The UCFs introduce novel elements to extend and contribute to the broader ecosystem, with five of them harmonized with existing 6G standardization and analysis efforts to strengthen the overall framework: *Collaborative Robots, Digital Twins, Fully Connected World, Trustworthy Environments* and *Immersive Experience*. Additionally, we identified three new UCFs that reflect Germany's unique vision for 6G: *Resilient Society*, focused on connectivity for public safety, security, and emergency response; *3D Mobility*, aimed at seamless communication of mobile devices especially in urban areas, but also across land, air, and sea; and *Environmental Awareness*, supporting sustainability through advanced monitoring leveraging new 6G features.

Using this categorization as a foundation, we then analyzed the specific requirements and developed key technical building blocks (TBBs) necessary for enabling the collected use cases. Aligned with ongoing project outputs, this framework extends the vision of 6G, providing a future-ready ecosystem to address complex societal and industry needs.

Firstly, we have found seven key TBB categories and 29 TBBs essential for the successful development of 6G technologies. These categories encompass integrative artificial intelligence (AI) solutions, comprehensive network systems, advanced network architectures, converged communication technologies, integrated cloud-edge ecosystem transformation, air interface technologies, and orchestration and management capabilities.

Our analysis reveals that integrating AI is surely expected to be crucial for enhancing network efficiency, reliability and user experience, as the processing may occur at various points within the network, including network functions, management functions, application servers, or even in the UE. Especially, “Digital Twin, Simulation and Data Fusion”, is seen as a critical solution for most UCFs. Comprehensive network systems emphasize the

importance for all UCFs of modular and service-oriented architectures composed of physical elements and functions to meet diverse application needs and scalability requirements. Advanced network architectures underline the demand for flexibility in service delivery, enabling seamless interoperation among various network types. In consequence, the advanced network architectures and connectivity solutions and the corresponding sub-TBBs are indicated as mandatory or beneficial for most UCF.

Furthermore, converged network systems and communication technologies illustrate the need for integration of traditional and innovative functionalities, such as sensing capabilities and quantum technologies, reflecting emerging application demands. The findings also highlight the importance of cloud-edge ecosystem advancements, which optimize data processing, storage techniques, and computing architectures, particularly for the UCFs *3D Mobility*, *Resilient Society* and *Immersive Experience*. Air interface technologies are deemed critical for supporting a wide range of frequency bands and various antenna and transceiver architectures, where especially advanced transceiver technologies are stated to be mandatory for several UCFs. Effective orchestration and management frameworks are identified as foundational for automating service provision and ensuring robust resource management across multiple operators. Particularly, the security and trust TBB have to be highlighted as most UCFs state the mandatory character of this TBB.

Each TBB is further categorized into three development phases, indicating their timelines for transitioning from optional to mandatory demands. Phase 1 defined from 2025 to 2028, representing the most urgent technologies that need to be/will be applied from the first release of 6G. Phase 2 corresponds to technologies expected to be standardized between 2028 and 2030. Phase 3 follows from 2030 and includes technologies that will be seen as futuristic and maybe beneficial for later usage but not currently mandatory. Overall, the insights drawn from the analysis emphasize the need for innovative, interconnected technologies to address the evolving challenges of 6G communication systems and ensure their successful implementation in various application domains.

Secondly, we present initial insights into the features critical for the adoption of 6G. While technical building blocks (TBBs) represent the technologies needed to fulfill 6G requirements, these features are specific characteristics demanded by individual use cases, emphasizing a user-centric perspective. We deduced 61 features as potential cornerstones for the 6G deployment from the collected use cases. The features are further grouped into the overarching categories *Architecture*, *Network Capabilities*, *Trustworthiness*, and *Regulation*. A detailed survey conducted with the use case authors revealed which features are most relevant to specific UCFs.

At a short glance, the features in the *Architecture* category mainly relate to predictability and flexibility guaranteed by network architectures. For example, network status information and performance predictability, adaptation and recovery capabilities, stand out in this category. *Network Capabilities* present a more diverse picture including several features that can be measured by specific Key Performance Indicators (KPIs), e.g., transmission time. Regarding this, for instance, the UCF *Fully Connected World* stands out with harsh requirements for transmission, update, and response time below 1 ms, as well as synchronization.

As their names already suggest, the *Trustworthiness* category is closely related to the UCFs *Resilient Society* and *Trustworthy Environments* that impose novel and enhanced trustworthiness requirements. Heterogeneity in the realization of features is apparent for fidelity, where demanded percentages varied from 70% to 99%. In line with findings of earlier initiatives, availability and message loss requirements exceed four 9s or 0s, respectively. While findings for *Regulation* are varying, a trend towards interoperability and flexible regulation can be observed, particularly by the UCFs *Fully Connected World*, *Environmental Awareness*, and *Trustworthy Environments*. Related to Hexa-X II, the European 6G flagship project, we have discussed the results of the feature analysis as well as with respect to use case families and TBBs.

Additionally, we introduce some key challenges for testing and measuring new 6G technology building blocks to bring them to market. The complexity of upcoming communication systems and the rise of AI with its data-driven approach change how technology building blocks are validated. The testing systems should adapt to that with functions such as enhanced end-to-end testing and scenario-based validation.

1 – Introduction

1.1 – Motivation

Communication systems are the central nervous system of a digital economy and society. The discussions on deploying 5G networks have highlighted the high relevance of technologies in mobile communications. To act in a sovereign manner, Germany and Europe need to play a vital role in shaping technology development and not just use technology. In shaping the technological foundations of 6G, Germany must take a solid role and act at the forefront of the ongoing international research. Central to this is, in particular, strengthening the cooperation of all relevant players.

The working group WG:Roadmap, as well as the overall 6G Platform Germany, ensures that research groups that are actively involved in mobile communications research (European and especially German industry and research institutes), but also non-actives, can contribute to the identification of 6G leading applications and requirements. The focus is on ensuring efficient harmonization of visions and concepts of the German-funded 6G projects with the aim of defining a uniform German vision. The necessary comprehensive and inclusive consideration of as many stakeholders, projects, and key parties as possible is part of the accompanying research activities of the working group. This takes into account that the definition of 6G is a dynamic process with currently still dynamically changing agendas.

The overarching goal of the working group is to align with ongoing international research and development efforts, contribute to standardization through collaboration with relevant bodies such as 3rd Generation Partnership Project (3GPP), and facilitate opportunities for participation by society and industry. This makes it mandatory to effectively communicate the current findings from the working group and present the most recent view on the identified 6G use cases (UCs) and use case families (UCFs), existing and novel technology building blocks (TBBs) needed to realize those use cases, as well as new requirements demanded by the use cases. Interim results of the working group were already provided for the alignment with 6G-SNS and 6G-IA in the context of the standardization discussions of 3GPP SA1.

The presented analyses are based on the inputs of the 33 6G-BMBF funded projects (18 industry projects, 7 resilience projects, 4 research hubs, 3 co-funding of AI-NET and the 6G Platform). Therefore, the results represent various project visions and a broad expertise, reaching from academia to industry perspectives and knowledge. The comprehensive scope of the white paper includes the richness of application areas such as manufacturing, healthcare, and agriculture and the visions of diverse contributors such as academic researchers, telecommunication companies, medical engineering companies, and microelectronics and chip designers. This reflects the overall 6G developments, challenges, and requirements from a wide perspective.

This paper's nature of being based on the inputs of ongoing BMBF-funded projects also sets a frame on how to interpret the statements in this paper and what to expect from 6G. First, since the respective projects are not finalized yet, the statements in this paper do not represent their final results or anticipate upcoming R&D results. Instead, it reflects their vision of a wide range of opportunities that 6G can enable in the near future. Second, with the previous generation 5G being a very sophisticated technology already, 6G emerges as an evolutionary step based on a solid technological basis with novel capabilities and different levels of progress in specific areas. Accordingly, this white paper presents several use cases that not only emerge with 6G technology but also include those envisioned for 5G that are now feasible with new 6G capabilities. Over these use cases, it examines new technological building blocks and challenging requirements that will potentially be encompassed and fulfilled by 6G. Additionally, the findings are discussed in relation to other 6G initiatives, standardization efforts, and projects, highlighting Germany's vision for the future of 6G.

1.2 – Methodology

The presented results and ideas were collected by the WG:Roadmap of the 6G Platform Germany. Within this working group, we aim to harmonize the German vision on use cases and provide indicators for pre-standardization. In November 2023, we sent the call for contributions for use cases to the 33 BMBF-funded 6G projects. These use cases are collected based on a standardized template, inspired by the 3GPP SA1 UC template. By the end of February 2024, we gathered 83 use cases out of 21 projects and formed three task forces (TFs) to analyze these use cases. The TFs have met weekly over 13 months, having 35 contributors, who concentrate on three main topics:

The *Harmonization* TF has harmonized various use cases by summarizing and merging them into more comprehensive UCFs based on a coherent and consistent structure. Initially, the *Harmonization* TF adopted an existing use case categorization from the Hexa-X-II consortium as a baseline, also to align with the on-going 6G development and standardization efforts.

Then, the TF enriched these (five) categories with additional use cases, and finally proposed three new UCFs, reflecting novel ideas from German academic and industrial contributors. The UCFs and their respective UCs are presented in Chapter 3 – Use Cases.

Secondly, the *Technical Building Blocks (TBB)* TF has concentrated on identifying the most relevant architecture blocks, considering the responses by the use case contributors and the existing blocks, e.g., defined by the Hexa-X and Hexa-X-II consortium. Furthermore, new building blocks were discussed to capture further novel building blocks. After considering internal WG:Roadmap feedback, the authors were again approached to highlight the need for their use cases concerning the defined TBBs. The results are displayed in 4 – Technical Building Blocks.

Lastly, the *Requirements* TF has identified the most relevant requirements and features, using on the one hand the input delivered by the use case contributors from academia and industry as well as the general understanding within the TF members. The TF has also conducted an extensive feedback survey among the use case contributors on the requirements of their individual use cases. The obtained results are described in detail in 5 – Features and Requirements.

Each task force has combined two main approaches: on the one hand, the findings from the existing 6G programs (with a focus on Hexa-X as the largest European project) and, on the other hand, the analysis of the German perspective from the provided use cases and feedback by the member projects of 6G Platform. Consequently, we have taken the existing 6G programs and projects as a reference to identify common grounds and differences and highlight our contributions, reflecting the view of Germany on 6G. Throughout the whole process, we have set multiple review cycles to get feedback from the use case contributors and the working group members. Besides these technical and organizational aspects, we prioritized open discussions and transparency to strengthen this white paper with diverse opinions and to adapt to changing circumstances with overall agreements effectively.

1.3 – Contributors

Over 170 participants, representing 26 of the 33 BMBF-funded 6G-projects, contributed to the white paper in its current form. This includes use case authors, reviewers and active task force members. More than 185 subscribers followed the activities of the WG:Roadmap. Over a period of more than a year, contributions were collected and discussed by the working group (in plenum and/or in the individual three taskforces). In consequence, the expertise of various experts from academia and industry of different research areas were involved and brought together. Emphasis was given to the active contributions of industry partners, especially SMEs, to reflect their needs for further standardization. In general, the discussions were open to all taskforce members, such that predefined opinions and directions were avoided.

1.4 – Structure

The white paper is structured as follows: After this introduction of the general information regarding motivation, methodology, assumptions, and expectations of the contributor's view, an outlook on 6G is given in 2 – Brief Outlook on 6G. This provides insights into the existing efforts and projects other than the activities in Germany presented in this paper. Our members' perspectives on the recent trends and developments are also highlighted in that chapter.

In 3 – Use Cases, we present several use cases under eight main UCFs. Chapter 4 – Technical Building Blocks analyzes the prominent TBBs for the respective UCFs and discusses their development phases through 6G standardization. Chapter 5 – Features and Requirements focuses on the new features and requirements of the presented UCFs.

The takeaways and additional details for UCFs, TBBs, and requirements are further presented in 6 – Discussion, especially in comparison with the European view, reflected by the findings of Hexa-X. This is supplemented by a discussion on the testing and measurement challenges for upcoming 6G networks in 7 – Test and Measurement Challenges for 6G Technology Building Blocks. Finally, we conclude the paper in 8 – Conclusion.

2 – Brief Outlook on 6G

2.1 – Current Efforts and Projects

Global 6G research efforts are accelerating, with key initiatives emerging across major regions (see Fig. 1). Leading countries like Japan, China, South Korea, and the USA are advancing through national and cross-national partnerships. In Asia, Japan's NICT collaborates with Germany's 6G Platform, supporting joint workshops, while China's IMT-2030 (6G) and South Korea's 6GForum push regional innovation. In North America, the Next G Alliance and NSF RINGS drive research in the USA, while India's TSDSI and India's Ministry of Communications, with the release "Bharat 6G Vision", provide a framework in South Asia. Additionally, international industry-led initiatives such as One6G, 6G AI, 6G SNS, and IOWN emphasize the global interest in developing a unified 6G vision.

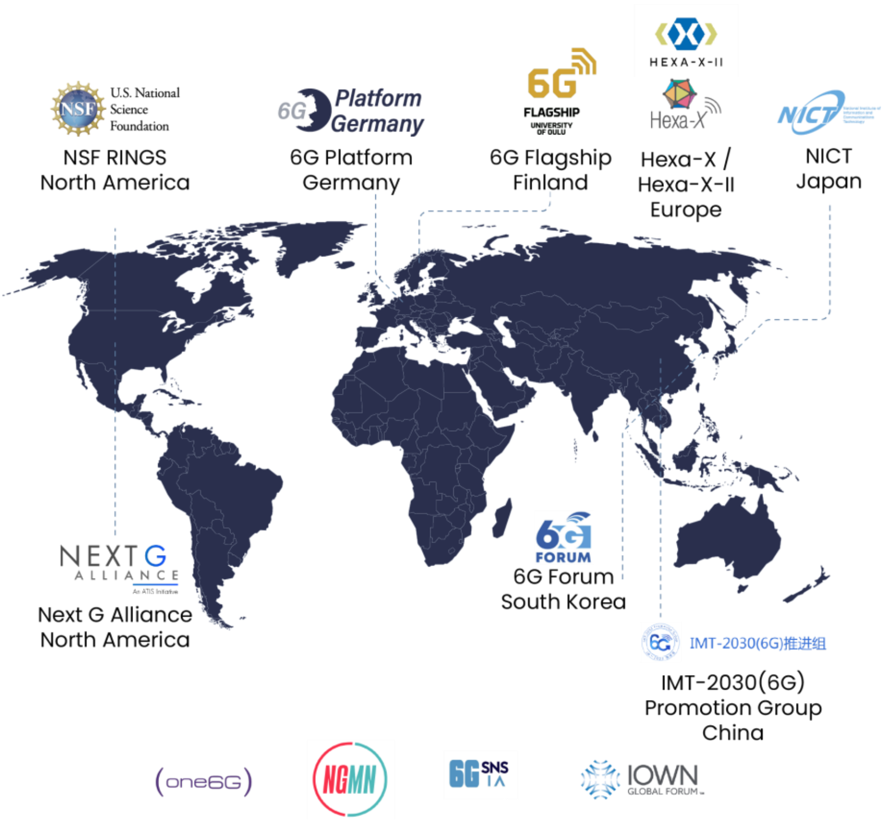

Fig. 1: Excerpt from 6G initiatives worldwide.

Furthermore, well-established organizations like the GSM Association (GSMA) and the Next Generation Mobile Networks Alliance (NGMN) are working on the development of 6G. Lastly, standardization organizations, such as European Telecommunications Standards Institute (ETSI) and International Telecommunications Union (ITU), are developing frameworks, requirements, and specifications for the 6G standardization process.

A central aspect of many of these initiatives is the exploration of use cases to envision applications, derive requirements, and address technology demands. The Next G Alliance categorizes its use cases into four main areas: *Network-Enabled Robotic and Autonomous Systems*, *Multi-Sensory XR*, *Distributed Sensing and Communications*, and *Personalized User Experiences* [1]. These categories cover diverse applications – from cooperating autonomous robots in the field to immersive experiences in gaming and remote operation/collaboration to wearable technologies that enhance public safety and inclusivity.

NGMN takes a similar approach, grouping use cases under *Enhanced Human Communication*, *Enhanced Machine Communication*, *Enabling Services*, and *Network Evolution* [2]. This classification aligns with the Next G Alliance in many aspects: Extended Reality (XR) fits under *Enhanced Human Communication*, while connected robotics and cobots align with *Enhanced Machine Communication*. NGMN also highlights digital healthcare and trusted service composition under *Enabling Services*, reflecting a focus on trustworthiness and security that also extends to their *Network Evolution* category, alongside goals like energy efficiency and artificial intelligence (AI) integration.

In Europe, significant efforts are underway through initiatives such as the flagship projects Hexa-X and Hexa-X-II, which are co-funded by the European Union and reflect a distinctly European perspective on 6G development. Hexa-X-II proposes six UCFs: *Immersive Experience*, *Collaborative Robots*, *Physical Awareness*, *Digital Twins*, *Fully Connected World*, and *Trusted Environments* [3]. Unique to Hexa-X-II is its emphasis on trustworthiness, dedicating a full category to *Trusted* Environments – a perspective distinct from other international initiatives. Hexa-X-II's other categories resonate with global themes: *Fully Connected World* aims to provide universal Internet access, similar to the Next G Alliance's *Distributed Sensing and Communications*; *Collaborative Robots* emphasize factory and field robot cooperation; *Digital Twins* support predictive maintenance and process management with AI; and *Immersive Experience* encompasses real-time, immersive applications like XR in education and gaming.

Further contributions to European 6G research are made by projects such as 6G Flagship and 6G Bridge in Finland, France's France 6G, Spain's España Digital 2026, Italy's Research and innovation on future Telecommunications systems and networks (Restart), the Netherlands's Future Network and Services and Germany's 6G BMBF initiative, represented by 6G Platform. With substantial funding of over 700 million Euros, these projects reinforce Europe's competitive position, especially through partnerships with industry bodies like 5G-ACIA and 5GAA.

Finally, to align national insights with European goals, our program collaborates with 6G SNS, which aggregates input from initiatives across Europe. Considering their broad scope and the involvement of several industry leaders and academic institutes, our analysis primarily focusses on aligning the German program's perspective with the European flagship projects, Hexa-X and Hexa-X-II.

2.2 – Trends and Developments

As the successor to 5G, 6G is poised to push the frontiers of telecommunications technology further, driving the development of new applications and enhancing the performance of existing ones, aligning with emerging consumer and industry trends. Beyond traditional data transmission, 6G introduces sensing capabilities that creates opportunities for applications that extend beyond pure communication. Additionally, 6G will transcend terrestrial limits, combining terrestrial, airborne, and spaceborne systems to establish a comprehensive network offering unprecedented levels of global connectivity. 6G networks will potentially embrace AI to optimize network operations and will provide a robust infrastructure that enables rapid and efficient access to AI capabilities across various use cases. Naturally, all these developments bring new legislation and regulation requirements.

Achieving these advancements must further align with sustainability goals, particularly in terms of energy efficiency. The increased adoption of IT and telecommunications necessitates reducing natural resource consumption, making sustainability a crucial driver in 6G development. Another challenge will be ensuring seamless integration and interoperability of all those new technologies.

2.2.1 – Consumer and Industry Trends

The ongoing development of 6G by global standards organizations like 3GPP and ITU is set to bring the new mobile internet standard by 2030.

This advancement aims primarily to address end-user needs by enhancing user experiences through ultra-high data throughput, improved connectivity, and immersive applications such as augmented and virtual reality (AR/VR). As the demand for data and connectivity continues to rise, new spectrum allocations—such as the potential deployment of higher frequencies like 6 GHz—will be crucial, especially in densely populated areas where existing spectrums up to 3.6 GHz may soon reach their limits.

The proliferation of connected devices within Smart Home and Smart City initiatives will further drive the adoption of IoT applications, demanding networks with self-connecting capabilities, seamless usability, and intelligent, adaptive services. This anticipated increase in network flexibility and responsiveness will be facilitated by network as a service (NaaS) models and an expanding cloud-native network infrastructure. These developments, including the use of Open Radio Access Networks (O-RAN) and Cloud RAN, will enable more efficient resource management and support AI and machine learning (ML) capabilities throughout the network stack. Advanced AI tools, particularly generative AI and natural language processing will personalize services, adapt to user preferences, and enhance operational efficiency.

Wearable devices are also expected to play a significant role in the future of health and wellness services by 2030, enabling real-time health monitoring and facilitating advanced health applications that improve healthcare delivery. Innovations in telemedicine and remote monitoring will enhance healthcare quality and accessibility, while in industrial contexts, non-public networks (NPNs) will support automation and smart manufacturing processes, optimizing logistics and ensuring precise, secure data exchange.

Additionally, 6G will likely transform education and training through AR and VR technologies, providing highly immersive, interactive experiences that can be utilized across sectors. As autonomous and remotely operated systems—including vehicles and drones—become increasingly common, there will be a need for reliable, on-demand communication services that deliver low latency and strict service level agreements (SLAs). Enhanced sensing capabilities within 6G networks will further ensure the safety and efficiency of these systems.

Smart Agriculture, as part of this technological evolution, will benefit significantly from improved connectivity. The ability to monitor and manage crops and livestock more precisely will support more sustainable and efficient agricultural practices, contributing to the broader application of 6G technologies in various industries and sectors.

Overall, 6G's expansive capabilities are set to redefine connectivity and digital services by 2030, creating a foundation for next-generation user experiences, industry applications, and innovative societal advancements.

2.2.2 – ITC Legislation and Regulation Development

The evolution of mobile technology brings regulatory challenges that will necessitate responsive national and EU legislation. The critical resource of the frequency spectrum requires international coordination among ITU-T, CEPT, and national regulatory bodies. To achieve connectivity goals, specific spectrum allocations for technologies such as terrestrial networks (TN), non-terrestrial networks (NTNs), and NPN networks are essential to enhance user experiences and maximize bitrates.

With AI and ML becoming integral to 6G network management, regulatory frameworks at the EU and national levels must establish standards for responsible and safe AI use. This includes upholding data privacy, where General Data Protection Regulation (GDPR) plays a pivotal role in ensuring transparent handling of personal data, particularly concerning privacy-sensitive applications within public and non-public networks.

Security considerations will require new regulations to protect against vulnerabilities introduced by AI. This includes enforcing robust encryption for user and control traffic, secure data storage, and protection against unauthorized access. To facilitate global interoperability, compliance with international standards and guidelines that address security and privacy will be crucial.

In line with the EU's sustainability objectives, 6G development must address national and EU targets for emissions reduction and energy efficiency. Regulatory bodies will need to mandate emissions and energy consumption reporting while promoting energy-efficient technologies. Additionally, 6G's accessibility and affordability for the general public are legislative priorities aimed at minimizing digital divides and enhancing inclusivity.

2.2.3 – Trustworthiness

According to ISO/IEC TS 5723:2022, trustworthiness is the "ability to meet stakeholders' expectations in a verifiable way". This is fundamental to the 6G vision, especially in contexts where system failures could result in direct human harm, such as robotic and autonomous applications. As 6G will integrate unprecedented sensing capabilities, potential privacy risks are heightened. Granular location tracking and sensitive data processing necessitate a robust privacy architecture, which must be designed to uphold both security and user trust. An overview of the key pillars for mitigating threats at the core trustworthiness nexus in 6G system design involving users, applications, infrastructures and their interdependencies is shown in Fig. 2.

The integration of NTNs in 6G, offering extended connectivity and resilience, also presents challenges, including intermittent connectivity and resource limitations specific to satellite-based components. Addressing these issues requires the development of advanced security protocols across physical and network layers. Furthermore, the convergence of security and safety in 6G applications demands resilience against quantum computing threats. Technologies such as Quantum Key Distribution (QKD), Post-Quantum Cryptography (PQC), and Quantum Random Number Generators (QRNG) are expected to strengthen 6G's security frameworks, safeguarding sensitive data and ensuring secure communication channels. The adoption of Physical Layer Security in tandem with advancements like massive Multiple Input Multiple Output (MIMO), Reconfigurable Intelligent Surfaces (RIS), and Visible Light Communication (VLC) will reinforce these protections.

AI will play a dual role in enhancing and challenging security within 6G networks. AI can strengthen network security through intent-based, context-aware automation, yet it introduces vulnerabilities such as model and data poisoning attacks. Given 6G's reliance on highly disaggregated, software-driven architectures, security will also depend on techniques such as component isolation, access control, and formal verification. The move to cloud-native architectures and NaaS will further support these resilience and security measures, facilitating scalability to meet future traffic demands. Confidential computing technologies, including Trusted Execution Environments and Remote Attestation, will be instrumental in establishing a zero-trust security model - one that minimizes trust assumptions and ensures a robust, resilient security architecture in 6G networks.

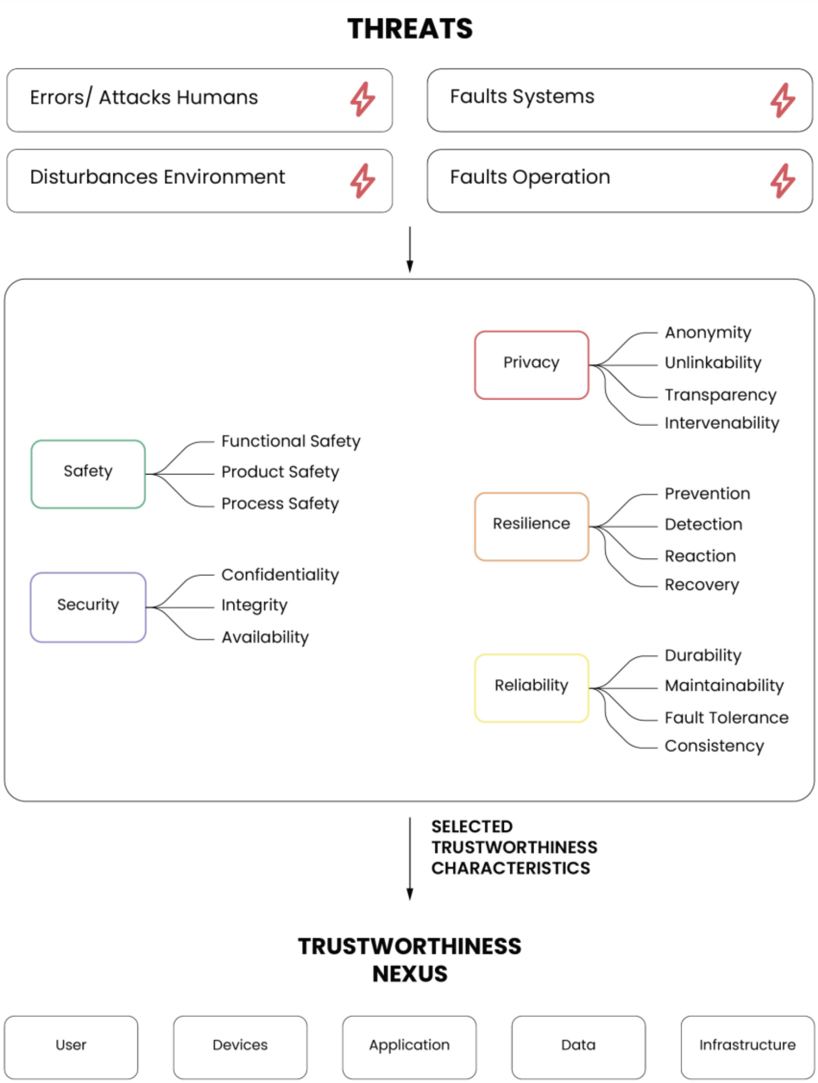

Fig. 2: Key trustworthiness pillars for mitigating threats at the trustworthiness nexus in 6G system design.

2.2.4 – Automation and Interoperability

The need for effective use of resources –especially the scarcest resource, the frequency spectrum– is growing constantly as more and more applications and use cases rely on wireless communication. This is underlined by the variety of use cases described in the following chapters of this white paper. Additionally, the growing necessity for automation – not only in the industrial domain – is a key motivator for ensuring systems work together seamlessly, as automation demands high levels of coordination and efficiency across various systems, which include communication systems.

Accordingly, interoperability is essential, enabling different systems, both application- and communication-related, and technologies to communicate and function without friction. It serves as a foundation for effective coexistence management, allowing diverse applications to operate harmoniously within shared environments. It is to be noted that coexistence is a state that does not refer primarily to the use of RF resources but to the applications served by wireless communication systems. For example, multiple applications coexist successfully if their operation is as desired, while on the RF level, interferences might happen, as long as the provided service, e.g., in terms of message loss rates or transmission times, does still suffice the application requirements. Only if at least one application's requirements are not met anymore will the coexistence state be disrupted. This perspective opens an enormous optimization potential, where, even in a joint manner, application and communication systems are able to adapt their behavior to enable the overall operation in a shared environment.

Automated collaborative coexistence management, as described in [4], builds on this foundation by monitoring real-time fluctuations in coexistence conditions and autonomously implementing solutions to maintain the required performance of wireless applications while ensuring the efficient use of critical spectrum resources. By facilitating smooth interactions, coexistence management not only improves resource efficiency but also supports the broader goals of automation, ensuring reliable performance across interconnected systems.

In this context, 6G holds promising developments in terms of effective resource usage and interoperability with non-3GPP technologies, i.e., a "network of network" concept.

2.2.5 – Sustainability

The ambitious targets of the European Green Deal for climate neutrality by 2050 emphasize the urgent need for sustainable infrastructure, especially in light of the increasing demand for data and connectivity. Various organizations, including standards development organizations (SDOs) like 3GPP, ISO, ETSI, and ITU-T, along with industry bodies like the GSMA and NGMN, are actively promoting sustainability in telecommunications. 6G presents an unprecedented opportunity to shape mobile networks by taking sustainability as a core principle from the outset, going beyond the adaptations of previous generations and leading to a model that is truly "sustainable by design".

One of the most energy-intensive aspects of mobile networks is the Radio Access Network (RAN), which is an important area for energy savings [5]. The GSMA, a global organization representing over 1000 mobile network operators (MNOs), identified the RAN to be responsible for 73% of MNOs' energy consumption [6]. In 5G, various energy-saving techniques have been standardized [7], [8]; however, they were integrated into an existing architecture not initially optimized for sustainability. With 6G, we have the chance to consider energy efficiency within RAN and network design more holistically.

6G networks could dynamically adapt to real-time network load conditions to minimize energy use in a way that was not feasible with previous generations. A study of power consumption of Open RAN (O-RAN) systems shows that nearly 80% of network traffic is concentrated in just 20% of sites [9], meaning that most sites often operate with minimal or no load. A 6G network could harness adaptive techniques to minimize power consumption significantly, for instance, temporarily deactivating unnecessary antennas or reducing the bandwidth in low-load scenarios. Additionally, advanced signaling techniques could be designed specifically to operate efficiently under low or no-load conditions, thus saving energy during off-peak hours.

By embedding these energy-efficient operations directly into network standards, 6G can set new benchmarks for sustainable telecommunications. Furthermore, through alignment with circular economy principles, such as end-of-life waste valorization, remanufacturing, and reuse of network equipment, 6G will support reduced resource consumption and longer equipment lifecycles, helping to curb electronic waste.

3 – Use Cases

6G is expected to transform multiple aspects of human life by combining numerous advanced technologies. This integration enables a wide variety of new use cases across different sectors. In work environments, 6G will support seamless intercommunication between autonomous robots, enhancing productivity, precision, and safety in industrial automation. On a societal level, 6G will boost public safety and security with smarter, more connected infrastructures, including real-time monitoring and response systems. The entertainment sector will undergo significant transformation with immersive next-generation AR/VR experiences, which 6G will foster by enabling real-time delivery of high amounts of hyper-realistic and interactive content. Transportation systems and cities will also become smarter, benefiting from real-time data exchange and decision-making that will optimize traffic management, energy use, and public services. Additionally, 6G will play a crucial role in sustainability efforts by providing the necessary tools for real-time environmental monitoring, energy-efficient systems, and fostering environmental awareness through interconnected smart solutions. These advancements will impact diverse domains, from agriculture and healthcare to business and smart cities, shaping a more connected, efficient, and intelligent future for society.

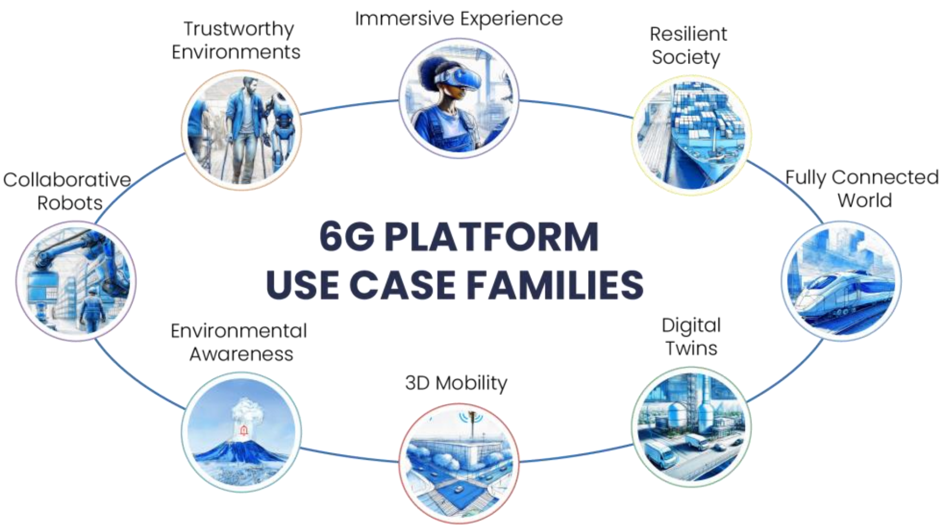

Fig. 3: Overview of the 6G Platform use case families.

This section explores various 6G use cases, categorized into eight distinct UCFs illustrated in Fig. 3. Five of these UCFs, namely *Collaborative Robots, Digital Twins, Fully Connected World, Trustworthy Environments,* and *Immersive Experience*, align with widely recognized use case categories from the prominent visionary 6G efforts, such as Hexa-X (and Hexa-X-II) and IMT-2030. This alignment ensures a comprehensive view of the expected global 6G applications. In addition to these, we introduce three new UCFs that reflect Germany's unique vision for the future of 6G: *Resilient Society, 3D Mobility*, and *Environmental Awareness*. They emphasize 6G Platform's focus on enhancing societal resilience through reliable communication, revolutionizing mobility on the ground and in the air, and addressing sustainability by promoting real-time environmental awareness. Together, these UCFs provide a holistic perspective on how 6G will transform various domains and address emerging global challenges.

3.1 – Collaborative Robots (CR)

Collaborative robots promise to revolutionize the way tasks are executed by allowing seamless, real-time joint execution of tasks by multiple robots, possibly interacting with human workers. These advanced systems ensure precise coordination and synchronization, fostering effective collaboration and a harmonious work environment in various domains. For instance, the deployment of autonomous mobile robots (AMRs), which can operate in groups or independently, can significantly improve the speed, efficiency, and operational safety in logistic centers, such as warehouses, container ports, and terminals.

For performing complex tasks autonomously, collaborative robots should exchange information in real-time to adjust their actions to avoid collisions and ensure the safety of their human counterparts. The requirement for their safe and reliable operation and intercommunication induces various new challenges. For instance, collaborating robots in rural agricultural areas require a predictable timing behavior with low latency and extensive coverage over geographically large areas. In contrast, interconnected AMRs in dense industrial facilities impose real-time and high reliability communication constraints to avoid potential safety or security incidents. To tackle those challenges, 6G will harmonize several ground and space technologies for connecting large distances, and sensing and AI technologies that are not available in the existing systems.

Fig. 4: Collaborative robots, empowered by reliable low-latency connectivity in 6G, enhance autonomy, and safety in human-machine interactions by enabling real-time and joint task execution in manufacturing and logistics.

3.1.1 – Autonomous Mobile Robots for Smart Factory

Industrial production plants are increasingly shifting towards full automation, in which AMRs efficiently navigate through complex and crowded environments, optimize their routes, and reduce the need for human labor, ultimately enhancing the overall productivity. The seamless exchange of information between AMRs, combined with their localization and environment sensing capabilities, and adaptive use of network-provided computation resources on demand are employed for efficient route planning, collision avoidance and task scheduling.

In order to implement a safe and efficient industrial production workflow, it is necessary to monitor and control machines with low latency and to ensure reliable communication between devices and humans. Beyond mobile (collaborating) nodes, this also applies to a high number of interconnected elements, such as potentially thousands of sensors placed along sorting and conveyor belts that communicate over the wireless medium. Here, 6G non-public networks can be a promising solution to ensure reliable connectivity for AMRs, limiting interference from external networks. Furthermore, several associated technologies in the context of 6G will be key enablers of this use case. The distributed and cell-free massive MIMO can improve coverage and reduce no-service zones, leading to better connectivity in dense production environments. It can also help to mitigate the effects of fading and interference, resulting in a more reliable and robust wireless connection. Utilizing low-latency connections in 6G networks, inter-communicating robots can navigate through complex surroundings with enhanced adaptability and precision, even under changing environmental conditions.

3.1.2 – Connectivity for Smart Agriculture

Smart agriculture refers to achieving a higher level of autonomy and efficient machine collaboration in the agricultural sector. In agricultural areas, drones, robotic harvesters, and agricultural workers collaborate to optimize crop management and irrigation with minimal human intervention. This requires reckoning with the changing environmental conditions and the specific needs of farmers, with real-time monitoring and decision-making, typically over large distances and with limited connectivity.

As an integral part of 6G, NTN, including drones, high- and low-altitude platform stations (HAPS/LAPS), and satellites can tackle connectivity challenges, where terrestrial base stations (BSs) cannot provide sufficient coverage in rural agricultural areas. Furthermore, the application of multi-access edge computing (MEC) to space-based and flying nodes will foster the integration of computing entities into communication infrastructure, combining the benefits of ubiquitous coverage and low latency applications.

Finally, since the available bandwidth becomes even more limited as a result of increasing number of UEs in 6G ecosystem, the use of semantics in communication makes it possible to reduce the data and energy consumption by only transmitting application-relevant information, leveraging the information known to all communication sides and eliminating redundancy. In smart agriculture, such context-awareness enables autonomous collaboration and intelligent decision-making that leads to an efficient farming process.

3.1.3 – Enhanced Safety for Industrial Environments

In smart factories, where human workers coexist with machines, safety zones need to be established around machines, paths and areas in industrial facilities that are perceived as hazardous for the people in their vicinity. The main purpose is to stop equipment and machine operation if an object or a human enters the protected safety zone. Traditionally, industrial robots are surrounded by a cabinet or a fence (physical safety measures), however, non-physical safety mechanisms are crucial to achieve the required safety standards in highly dynamic and interactive factory settings of the future.

With integrated sensing and communication (ISAC) introduced to the network, 6G systems can be able to form dynamic safety zones by sensing and tracking objects in a particular area. Non-public 6G networks in industrial environments can especially benefit from ISAC given the relatively large radio resource pool at their disposal. The sensed data from the robots, base stations, and dedicated sensing equipment can be fused to generate a comprehensive view of the environment and the objects within. AI- and MEC-native 6G ecosystem can enable edge robotics, by the capability of analyzing huge amounts of sensing data effectively at the edge, to orchestrate the overall industrial system with enhanced safety. This foremost requires robust, reliable, and real-time wireless communication, which is specifically targeted by 6G.

3.2 – Environmental Awareness (EA)

Environmental awareness is vital to monitoring and addressing global natural changes by proposing and taking proper and effective actions ensuring appropriate and sustainable conditions for life. Gathering sensory data through environmental observation could help in the early detection and timely mitigation of disasters such as fires, gas pipeline leakages, and volcanic eruptions in the short term. In the long term, it provides an invaluable foundation towards understanding Earth's climate dynamics and overall living conditions. Moreover, an effective environmental observation provides invaluable information to enhance global social and economic strategies such as agricultural planning, building climate-resilient infrastructure, and creating precise routes and schedules for transportation.

Given the scale of the Earth and numerous natural phenomena happening simultaneously on any scale, it is enormously challenging to collect, correlate, fuse, and interpret environmental data effectively. Therefore, environmental observation requires scores of ground, air, and space nodes with varying sensing capabilities. Besides, a sheer amount of data should be shared and processed timely over arbitrary distances to tackle spontaneous environmental changes. Embracing satellite, airborne, and terrestrial technologies distributed all over the globe and combined with sensing capabilities, 6G provides extended coverage and increases environmental visibility for an enhanced Earth observation.

Fig. 5: Environmental awareness will advance via novel sensing capabilities in 6G, providing essential data for disaster mitigation, climate monitoring and resilience, and urban planning.

3.2.1 – Advanced Earth Observatory System

Synthetic aperture radar (SAR)-based earth observation from airborne or spaceborne platforms has become a rapidly growing field of application over the last decade. The continuous acquisition and processing of these SAR data allows for a better understanding of the changes Earth undergoes, for example by deriving highly accurate surface models in rural areas for monitoring glaciers or coastal areas or in regions that are difficult to access by systems operating in visible spectrum.

6G can pave the way for an advanced Earth observatory system by enriching the existing SAR data with improved and extended sensing capabilities. As a part of extensive 6G ubiquitous networking, different nodes including satellites, HAPs, airplanes, drones, and IoT devices, meticulously gather measurements of various environmental parameters such as greenhouse gases, temperature, air pressure, humidity, solar energy reaching Earth, and light reflected from its surface. These nodes, either as user equipment (UE) or BSs, leverage novel waveforms in weather-sensitive frequency bands that will potentially be enabled in 6G. Weather sensing gives geologic, hydrologic or meteorologic institutions benefit to access detailed information with lower sparsity about the weather and its impact. Furthermore, 6G catalyze the seamless interconnection of these components with predictable timing behavior with low latency and high throughput communication capabilities, ensuring the most recent data, leading to real-time adaptation and mitigation strategies in response to changing Earth conditions.

3.2.2 – Sensing-enhanced Communication at Changing Environmental Conditions

Since mobile cellular networks cover most of the populated areas on land surface, the advent of the ISAC in 6G will make it possible to use the mobile networks to sense not only the location and trajectory of mobile user, but also their surroundings (in a privacy-preserving manner), weather condition and their impact on the environment. This helps acquire real-time information about the environment wherever the 6G infrastructure and UEs reach out. Gaining knowledge of the radio environment may be a tremendous advantage to MNOs for adjusting and optimizing the communication performance of the primary system, i.e., sensing enhanced communication. MNOs can reconfigure beamforming, handovers, bandwidth allocation or assisted physical layer security etc., according to the (natural) environmental changes in any scale. The sensed information can be used to forecast communication channel quality as well as to detect obstacles, for instance, after a natural disaster that may block the connection, thus helping to avoid connectivity disruptions.

3.3 – Digital Twins (DT)

A digital twin is the digital representation of complex physical assets and operations. It enables the digital reproduction of the behavior of such complex operations in different systems and domains like industrial facilities, smart cities, and construction sites to enhance their functionalities, which shift heavily towards full automation. It helps to analyze those systems via simulations in digital domain, monitor and control their physical assets in real-time, and develop advanced diagnostics mechanisms for their safety and security.

To achieve the full potential of digital twins, ubiquitous network connectivity within the target system is essential for collecting a high amount of data from various sources such as sensors, tags, network components, and external data models. Continuous and high-accuracy data collection is additionally challenging in dynamic environments such as industrial facilities where mobile and static components coexist. Besides, making and performing real-time decisions based on the analysis of the collected data requires time-sensitive communication, especially in industrial environments.

Fig. 6: Digital twins facilitate advanced analysis and maintenance for complex systems by enabling real-time monitoring and diagnostics, leveraging 6G's targeted high-speed and low-latency connectivity.

Leveraging environmental sensing via ISAC, 6G enables acquiring high-precision data even in dynamic and dense environments, e.g., smart factories, to feed complex digital twins. Increased connectivity and data rate in 6G networks are also prominent in building accurate and comprehensive digital representations of systems based on extensive amounts of data.

3.3.1 – 6G for Real-time Industrial Digital Twins

Industrial production has been shifting towards full automation with AI-driven robotic systems. Such intelligent systems cannot only thrive for increasing efficiency but should also consider safety in dynamic human-machine integration. This requires adapting mobile and interconnected cyber-physical components to the changes in dynamic environments with high sensitivity. Moreover, these adaptations should be able to respond to stringent latency requirements in complex facilities such as Supervisory Control and Data Acquisition (SCADA) systems including programmable logic controller (PLC) and field levels, and additional machine tools, robots, central servers, wearables, etc. Digital twins help to acquire a system-level view of all such interconnected components and reconfigure during operation for improved process control and accurate position tracking. This, however, imposes the fast transmission of large amounts of data for control, modelling, and update information to and from central systems. 6G targets to provide high data rates and low latency to deploy real-time digital twins that can control industrial systems with deterministic timing behavior. Indoor broadband wireless transmission in D-band (110–170 GHz) enables feeding digital twins with sufficient, and real-time information as well as ultra-high data rates over short distances or combined with beamforming ability in dynamic human-machine communication scenarios.

3.3.2 – Enabling Brownfield Sensor Systems

Most industrial facilities are brownfield systems, featuring machinery that has been in place for several years. To leverage state-of-the-art control and data acquisition technologies, additional sensors can be integrated into the existing machines. These sensors enable the implementation of new control tasks and the creation of digital twins of the machinery units, based on the collected sensory data. However, they also induce diverse requirements for latency, data rate, and reliability in communication, especially when attached to mobile components, where constantly changing environmental conditions further complicate safe and efficient operation.

The 6G ecosystem aims for promoting flexibility to dynamically manage and reconfigure subnetworks to accommodate the changing demands of a multi-sensor platform. The high data rate and low latency capabilities of 6G make it ideal for transmitting vast amounts of sensor data to central digital twin instances. Since these digital twins rely on continuous, real-time data from distributed sensors, 6G's robust wireless connectivity ensures efficient and reliable data transfer. Moreover, 6G networks incorporate older, non-3GPP communication technologies found in brownfield systems, facilitating seamless operation between new and legacy infrastructure. This enables the collection of additional data over various available technologies to build more representative digital twins.

3.3.3 – Advanced Predictive Maintenance for Industrial Systems

Predictive maintenance involves continuous monitoring of equipment condition to predict their downtime, maintenance period, and potential anomaly. This reduces maintenance costs and maximizes equipment lifespan. Accordingly, one of the prominent roles of digital twins in smart manufacturing is to leverage ML and/or AI capabilities to analyze the collected data from several interconnected components, render its spatial representation, detect irregularities in otherwise nominal operational patterns, and identify the types and locations of impending failures. For instance, it is possible to detect a malfunction in the manufacturing equipment by analyzing their acoustic noise spectrums, where irregular noises manifest themselves as vibrations on equipment surface and can be detected by angle- and distance-resolved Doppler measurement of radio frequency (RF) sensing system. An indoor ISAC-enabled 6G network can be highly effective for these scenarios when RAN nodes and UEs collect RF sensing data continuously. Eventually, this constitutes an additional information layer for digital twins to implement advanced predictive maintenance systems in smart manufacturing.

3.3.4 – Network-assisted Digital Twins in Smart Manufacturing

In manufacturing, several interconnected applications such as monitoring and cloud-based control mechanisms rely on wireless communication and impose various requirements regarding data rates, timing behavior, resilience and mobility. These requirements change over time depending on the manufacturing production flow, e.g., during the production, transportation, and delivery of goods. The resources in the mobile communication environment should be configured flexibly to adapt according to the changing needs; thus, manufacturing and communication systems should interact continuously. When the configuration of the manufacturing applications is represented within digital twins, such an interaction can be achieved by collaborating digital twins and the cellular network. This includes exchanging traffic profiles, quality of service (QoS) demands, positioning information, and achievable performance KPIs, etc.

Besides inheriting traditional channel state estimation techniques, 6G will offer enhanced capabilities for sensing the surrounding environment, which can then be to develop channel charting models. These models help reduce the complexity of managing vast amounts of network data. When implemented within the network's digital twin, channel charting brings enhanced context awareness to various network management applications, improving data efficiency and optimizing decision-making processes for both network and manufacturing resources.

3.4 – Fully Connected World (FCW)

The previous generations of mobile networks have made significant achievements in fulfilling challenging coverage and QoS requirements of numerous interconnected systems all over the world. However, agricultural fields and rural areas with low population density still lack coverage, even in developed countries. Some critical systems, such as airplanes and maritime vessels, cannot utilize the existing cellular connectivity either, which is mainly dependent on terrestrial infrastructure. Besides, rapidly and continuously escalating connectivity demands have been pushing throughput and time behavior requirements beyond the capabilities of existing cellular networks even under broad network coverage. For instance, the number of connected Internet of Things (IoT) devices is expected to increase from 15 billion in 2023 to 38 billion in 2029 [10], possibly imposing various QoS requirements. Similarly, more and more data demanding applications (video streaming, industrial automation, virtual reality, etc.) boost the required data rates to be supported by future wireless communication systems.

Fig. 7: Fully connected world envisions locally and globally connected network of networks, integrating 6G-enabled ground, air, and space nodes to ensure seamless ubiquitous access and global coverage.

6G introduces a vision of a unified 3D network architecture that transcends the conventional integration of terrestrial and NTNs and sets the stage for a fully connected world. While current standardization efforts aim to integrate NTNs (such as satellites, unmanned aerial vehicles (UAVs), and HAPS) into terrestrial networks, this approach primarily focuses on enhancing connectivity between these distinct domains. In contrast, the unified 3D network envisions a seamless fusion of space, aerial, and ground-based segments into a single, cohesive architecture. Additionally, the incorporation of AI within 6G enhances the orchestration of this comprehensive network, enabling adaptive resource management, real-time optimization, and on-demand provisioning through mobile base stations and nomadic networks.

3.4.1 – 3D Networks

By combining terrestrial, airborne and orbital systems into one conglomerate "network of networks", the specific advantages of all these systems are combined to create a new type of network with 3D coverage across land, air and sea, even in areas that are currently considered white spots (no coverage at all) or grey spots (insufficient coverage/capacity for certain applications). The 3D networks in 6G will leverage HAPS (e.g., stratospheric gliders at 20 km – 50 km) and LAPS (drones, blips, zeppelins, etc.) with high-gain antennas able to reach TN nodes and end devices. This extends TNs with dynamic adaptation capability to exceptional network demand caused by e.g., disasters, public events, etc. Furthermore, low, medium, and geostationary earth orbit (LEO, MEO and GEO) BSs in the 6G ecosystem lead to truly global coverage, complementing terrestrial connectivity, where it is no longer available. This provides an extensive, resilient communication infrastructure capable of extending connectivity to remote and underserved areas and supporting high-mobility scenarios.

Continuous Connectivity for Transportation

Transportation and shipping vehicles frequently traverse regions with low or no connectivity, posing significant challenges for communication, especially in emergencies, and diminishing the overall passenger experience. While modern trains, such as the Intercity Express (ICE), provide Internet-connected Wi-Fi for infotainment, their connectivity is often restricted to populated areas, leaving vast stretches of travel inadequately served. For such scenarios, the unified 3D network architecture ensures uninterrupted communication by dynamically leveraging resources across space, aerial, and ground-based networks. In this context, high-speed vehicles stand to benefit significantly from the 3D network's ability to maintain continuous, reliable connectivity across long distances, even in areas where terrestrial coverage is sparse or unavailable.

Extended Coverage for Remote Areas

Industries operating in remote locations, such as agriculture, mining, and construction, rely heavily on autonomous, interconnected machines to achieve efficiency. While incorporating NTNs with terrestrial base stations extends connectivity to these remote areas, it primarily offers enhanced coverage and reliability through redundant links. This traditional approach provides options for connectivity but treats terrestrial and non-terrestrial components as separate domains. The unified 3D network architecture goes beyond that and allows interconnected systems, such as IoT nodes in a farm field, to make autonomous, real-time decisions on the optimal connectivity option, whether through ground-based or non-terrestrial base stations, based on parameters such as data rate demands, latency requirements, energy consumption, and battery status. Moreover, the unified 3D network enables NTNs to serve as efficient backhaul solutions for private 6G networks, ensuring reliable and adaptable communication even in the most remote and challenging environments.

3.4.2 – Advanced Wireless Backhaul Links

Connecting multitudes of mobile devices requires an increasing number of cellular cells, each covering only a small area, to offer the requested high data rates to all users. Each of these cells has to be connected via a backhaul link to the data network of a mobile service provider. A fiber connection is not always a viable option due to infrastructural complexity and maintenance cost. In 5G networks, wireless backhauling using millimeter wave (mmWave) links in the E-band (71–76 GHz and 81–86 GHz) has proven effective, facilitating the rapid deployment of new networks and improving availability. However, adopting these links for backhauling remains limited in certain regions, which the respective frequency bands are already heavily utilized.

6G networks will leverage new technologies for wireless backhaul links to overcome these situations. Flexible multi-antenna beam forming systems, with a large number of antennas in high frequency ranges from 300 GHz to 3 THz offer huge bandwidths of several tens of GHz to address increasing connectivity demands. For industry, wireless backhaul links can be used to provide high speed connectivity between geographically separated facilities without costly construction works. Additionally, in computing and data centers, 6G should enable point-to-point links at RFs beyond 100 GHz, such as in D-band (110-170 GHz) or H-band (220-325 GHz) to replace fiber connections. In conjunction with one- or two-dimensional electronic or quasi-optical beam steering, point-to-point and multi-hop wireless links can be implemented between computer racks, leveraging flexibility via software-based configuration as well.

3.4.3 – On-demand and Nomadic Networks

On-demand and nomadic networks enable spatially mobile BSs to be deployed dynamically wherever and whenever necessary. For instance, in agriculture, farmers can rent and operate a nomadic network as a mobile, on-demand wireless network within a specific geographic zone, enabling precise planning of crop cultivation. Furthermore, from an MNO perspective, nomadic networks can be operated with a pay-as-you-go paradigm, reducing both operational and capital expenditures, and promoting more sustainable information and communication technologies. Alongside such benefits, designing effective architectures, technologies, and mechanisms for automated interaction between on-demand nomadic access networks and a permanent terrestrial and NTNs imposes many challenges. Several other questions regarding frequency allocation between adjacent on-demand networks, facilitating trusted data exchange and time-limited licensing, are crucial points in the realization of nomadic networks. In 6G, dynamic backhaul regulation and implementation through O-RAN technologies, NTNs, and automatic licensing of private networks can effectively tackle these questions. This also encourages MNOs to develop a relatively simpler and flexible network infrastructure with minimal dependence on wired backhauling.

3.4.4 – Underlayer Networks in Industrial and Manufacturing Systems

With the increasing digitalization and interconnectedness of manufacturing systems, specialized underlayer networks have emerged to meet the requirements of various applications. For instance, in an automated factory, automated guided vehicles (AGVs) and robots need ultra-reliable and low latency communication (URLLC) for their cooperative tasks and enhanced mobile broadband (eMBB) to communicate with the controllers at for an overall route planning and navigation. This requires a network architecture leveraging and combining relevant wireless technologies to fulfill both URLLC and eMBB requirements.

The 6G ecosystem will facilitate the seamless integration of several technologies, e.g., Li-Fi or Wi-Fi, to design underlayer networks that fulfill the specific demands of interconnected and autonomous systems in manufacturing. This concept improves spectral efficiency by dividing the available bandwidth to enable underlayer networks for different use cases. In the aforementioned example, the URLLC network can be realized by any 3GPP or non-3GPP technology and the eMBB network is a 6G non-public network. An intelligent 6G controller can handle multiple radio access technologies within underlayer networks, e.g., having a limited bandwidth and coverage in the size of picocells around a few square meters. URLLC networks only operate if necessary and are managed by the 6G non-public network (e.g., dynamic activation upon resource requests). This controller should also handle traffic steering over multiple networks in a specific coverage area.

3.5 – Trustworthy Environments (TE)

Trustworthy environments are technological ecosystems that prioritize security, privacy, and reliability, especially for human-centric services, where the safety of human life is paramount. They are usually complex environments where IT services, cyber-physical systems, and advanced networked applications serve and are used by humans with strict safety and security requirements. In healthcare and elderly care, for example, several interconnected sensors should communicate with the highest reliability to instrument and assist medication management and support daily activities of patients and elders. This communication should also comply with strict privacy and security regulations to protect people’s sensitive information. Another example is smart industrial facilities that should ensure the secure and reliable operation of many interconnected and autonomous machines without jeopardizing the safety of human workers. This requires resilience and integrity of these machines in case of failures, malfunctions, and malicious attacks.

6G's transformative potential will be evident in remote healthcare, such as telemedicine, where near-deterministic communication across the globe is a necessity. Additionally, 6G's capability to enable ISAC can significantly enhance safety-critical scenarios, from real-time patient monitoring in hospitals to inspecting machinery conditions in factories.

3.5.1 – Autonomous Healthcare through ISAC

Emerging autonomous systems, brain-computer interfaces, implants, wearables, and robots are instrumental in revolutionizing elderly care and remote healthcare. These technologies can provide crucial support in daily activities, assisting with diverse tasks, medication management, and even possible companionship to people. However, they impose strict communication requirements in terms of timing behavior and throughput to ensure timely and high-precision data exchange to ensure the safety of people.

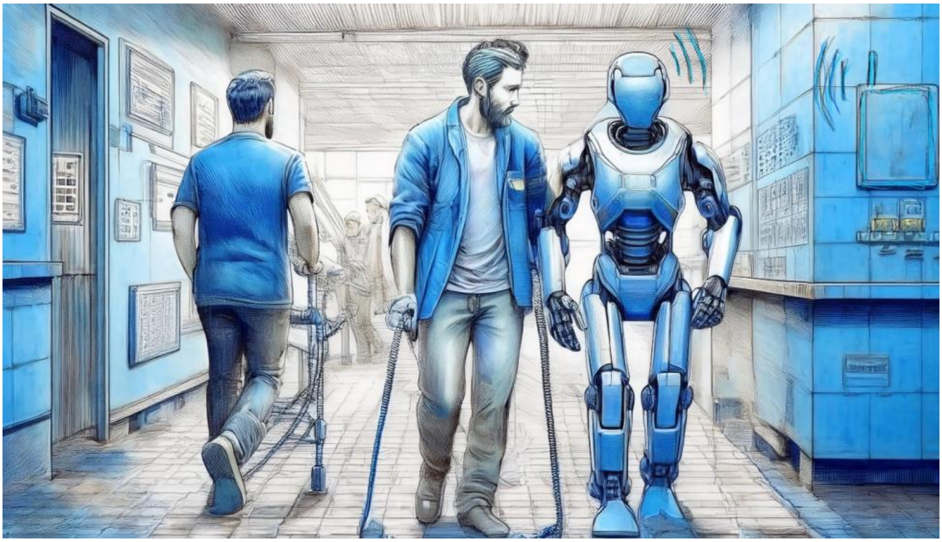

Fig. 8: Trustworthy environments prioritize security, privacy, and reliability for ensuring safety in human-centric services and safety-critical systems, empowered by deterministic communication and advanced sensing features in 6G.

6G offers high data rates, low latency, and integrated sensing capabilities that collectively enable real-time remote monitoring of patient health data from wearable and implanted devices. Enabling ISAC, 6G can allow for seamless data exchange between medical devices while simultaneously monitoring patients' activities and vital signs using the same signals. Moreover, this can empower intelligent healthcare applications like automated disease detection, smart hospital management, and personalized treatment recommendations using AI and digital twins as an integral part of 6G ecosystem. ISAC can also take a crucial role in intensive care units (ICUs) to detect critical changes in a patient's health and ensure immediate intervention, either by human staff or intelligent machines. Similarly, in private properties, medical emergencies of people or pets could be recognized by assessing irregular patterns, for example in the movements of the monitored subjects.

3.5.2 – Communication in Pandemic and First Response Scenarios

Global health emergencies like COVID-19 require immediate attention from international health experts. This necessitates vast amounts of medical data from various sources and quality, including high-resolution images, real-time genome sequencing data, and live video streams from outbreak zones, that can be shared globally with negligible delay while being trustworthy. Teleoperations in such situations may require collaboration via VR goggles for between medical operators, which impose strictly time-sensitive and reliable communication. For these scenarios, 6G promises high data transmission rates with more reliable connections, even in remote or traditionally under-served areas enabling NTN. This reliability ensures continuous and uninterrupted communication among international teams no matter whether they are stationary or mobile.

3.5.3 – 6G as a Security Provider for Industrial Applications

Industrial autonomation machinery has a significantly longer life cycle than IT technologies leading to a high number of brown field applications. A typical example is rail guided systems like skid platforms or electrified monorail systems (EMS) that use a variety of proprietary protocols usually with insufficient security measures due to lack of sufficient processing power. In any case, adding security mechanisms is necessary to adhere to recent regulatory requirements. 6G networks can provide security mechanisms for taking that burden of applications. For instance, authentication and encryption functions can be simply handled by 6G over a dedicated interface between the application server and the UE. Furthermore, 6G can leverage increased configuration flexibility to provide trust zones along application borders that are finely adjustable according to the application needs.

More complex and connected facilities with huge amounts of data traffic may require additional and more advanced security mechanisms. This imposes more effective countermeasures, i.e., intelligent distributed network anomaly detection systems coping with ultra-fast data transmission. Therefore, reconfigurable and programmable security hardware and software modules will potentially become an integral part of 6G ecosystems.

3.5.4 – Ultra-reliable In-vehicle Wireless Networks

In today's typical vehicular Electrical/Electronic (E/E) architectures, communication between all electronic control units (ECUs), sensors and actuators are implemented with dedicated and almost exclusively wired networking technologies such as automotive Ethernet. Although such physical wiring helps for achieving high data rates and reliability, it significantly increases the design complexity, weight, and cost of vehicles. ECUs have been already equipped with wireless technologies to establish V2X communication. Beyond this, 6G might find future application in all remaining layers of the E/E architecture, enabling in-vehicle wireless connectivity. Firstly, it can achieve URLLC between in-vehicle components, leveraging flexible and AI-based resource management mechanisms to address the distinct requirements of several in-vehicle applications. They can also tackle relatively high deployment density in in-vehicle networks to handle potential interference and ensure scalability. For additional reliability in case of safety and security incidents, having multiple ECUs acting as 6G gateways or BSs can enable multi-connectivity, assuming real-time diagnostics and handover mechanisms enabled by the 6G ecosystem.

3.6 – Immersive Experience (IE)

Extended reality (XR) applications, including virtual and augmented reality (VR/AR), have evolved from traditional visual and auditory multimedia applications to completely new immersive experiences. For instance, gamers with AR- or VR-capable devices can actively participate in virtual gaming environments, enjoying enhanced realism and interactivity. Moreover, XR devices integrated with new sensors enable a better perception and control of digitally extended environments and lead to more realistic and engaging holographic communication that could soon replace traditional video calls. Another prominent example is teleoperation, where human teleoperators can remotely control robots and machines with immersive perception. These advancements remove the borders between virtual and physical reality, creating a more realistic and captivating multimedia experience.

However, achieving such immersive experiences requires processing a significant amount of data, including sensory information from the physical environment and digital data from the virtual worlds. This data needs to be collected and processed not only in real-time but also with minimum jitter for the most realistic virtual experience. 6G, with its focus on predictable timing behavior even under mobile scenarios, is a key player in achieving immersive experiences. By integrating communication and sensing, 6G enhances AR and XR technologies with immediate sensory data from the physical environment. Furthermore, 6G can effectively leverage edge and fog computing resources with recent AI-driven technologies to support the real-time processing requirements of such data-intensive applications.

Fig. 9: Immersive experiences in 6G will evolve XR, VR, and holographic communication, enabling hyper-realistic, interactive environments through low latency communication AI-driven processing for multimedia, business, and industrial applications.

3.6.1 – Holographic Communication and Telepresence

The COVID-19 pandemic accelerated the adoption of remote working and monitoring, demonstrating the importance of remote communication and automation in maintaining business continuity. While current technologies like video conferencing have limitations, holographic video communication holds great promise for enhancing user experience. However, it requires processing a sheer volume of data generated and processed in real-time, which exceeds the capabilities of existing networks, especially if holographic communication is adopted in a broader range of applications.

As part of the 6G ecosystem, innovative 3D and volumetric hologram technologies with cellular communication capabilities could offer users immersive experiences in different locations. With 6G's high data rates, users can enjoy seamless, real-time connectivity as they move freely outdoors, indoors, and even in vehicles, enhancing telepresence interactions. This connectivity is especially critical for linking XR/AR devices with edge and cloud platforms to offload computational tasks efficiently. Additionally, 6G-enabled ISAC can significantly elevate the precision and realism of immersive applications by capturing richer, multi-dimensional data from the physical world.

3.6.2 – Enterprise and Industrial Immersive Experience

The adoption of XR devices, such as head-mounted displays (HMDs), is hindered by factors like affordability and end-consumer behavior. While XR devices with integrated cellular modems are not yet commercially available, ongoing efforts are being made to address this gap. Looking ahead to 6G, XR continues to be a significant application, particularly in the workplace context where 6G non-public networks are already in operation. These wearables not only provide hands-free access to data but also offer functionalities like barcode scanning and integration with Enterprise Resource Planning (ERP) systems, streamlining processes and improving operational efficiency. Wearables equipped with XR capabilities enhance employee productivity by providing real-time guidance and information, while technologies like ISAC further enhance workplace safety and security. The integration of NTNs and satellites in 6G networks is expected to expand mobile broadband access, particularly in remote areas, further bolstering the potential for XR end-consumer applications. By bridging the physical and digital worlds, 6G empowers enterprises and industries to boost productivity, minimize downtime, and make data-driven decisions in dynamic and data-rich environments.

3.6.3 – Immersive Teleoperation

Teleoperation of vehicles and robots has attracted a lot of new attention recently, for example in relation to automated driving or teleoperated robots in logistics or rescue scenarios. However, fully autonomous behavior of robots and vehicles is still facing many obstacles before deployment at scale and is therefore perceived rather as a long-term vision than a medium-term reality for many complex and safety-critical scenarios. Often, a work split between autonomous behavior and teleoperation is required: while “regular” situations can be handled autonomously, very challenging situations and tasks should be assisted by experienced human operators, which remotely control the respective robots or vehicles. The key precondition for safe teleoperation is highly reliable wireless communication links that can be trusted under any circumstances. Enabling large-scale terrestrial and non-terrestrial coverage, 6G will most likely offer an uninterrupted end-to-end communication medium to realize high reliability in teleoperation. It can also enable fully immersive perception and control, e.g., high resolution, 360° views of the environment etc., at high data rates and predictable timing behavior with low latency, further complemented by newly available sensing data from ISAC.

3.6.4 – Network-assisted Multimedia Applications

Rapidly increasing multimedia, including VR and AR applications, and streaming services impose various QoS requirements regarding data volumes and communication latency. The service providers have, however, a very limited knowledge of how network operators handle data routing and connectivity over the underlying network infrastructure. This requires a joint configuration between multimedia services and network operations. For example, a streaming service with numerous users in varying and remote areas (regarding connectivity) would need a smart network provisioning to optimize the user experience in terms of stream quality, bitrate, resolution etc. This could be further extended to distributing and offloading application instances over different parts of the network according to the user locations and network conditions. 6G ecosystem can provide several network telemetry services to assist the major service providers for autonomous distribution of service instances. Besides, in the context of "network of networks", 6G infrastructure can be configured dynamically to adapt to the occasional changes in service demands.

3.7 – Resilient Society (RS)

In an increasingly interconnected world, resilience (in a societal context) refers to the capability of a society to withstand, adapt, and quickly recover from various disruptions such as cyber-attacks and natural disasters. A resilient society should be equipped with several proactive and reactive countermeasures against a broad range of potential illegal activities on land, sea and air, including trespassing, robbery, smuggling, and terrorism, especially targeting critical infrastructures and assets. These infrastructures and assets, such as power grids, renewable energy sources, and public transportation vehicles, are often widely scattered over large geographical areas in a decentralized fashion. This requires more extensive monitoring and protection mechanisms compared to the existing protection systems covering only close proximity. Another significant challenge is guaranteeing the intra- and inter-connectivity of critical assets even under harsh safety and security incidents like earthquakes or well-calibrated attacks.

Fig. 10: Resilient society in 6G era will achieve advanced public safety and security, leveraging several technologies potentially taking place in 6G and integrated sensing for improved disaster recovery and protecting large-scale critical assets.

6G will potentially leverage advanced sensing capabilities across ground, air, and space communication units to enable extended, high-precision observability over large-scale public assets. Furthermore, 6G-enabled NTN components support aerial and maritime monitoring of remote and spacious critical infrastructure. Finally, while emerging quantum technologies potentially embraced by 6G can enhance the security of numerous interconnected public assets, increasing the reconfigurability of 6G radio technologies improves their adaptation and recovery capabilities in disaster scenarios.

3.7.1 – Public Safety and Critical Infrastructure Protection

Public safety encompasses the protection of numerous inevitable aspects of daily life such as public events, transportation, and private homes. Critical infrastructure like BSs, wind turbines, power distributions networks as well as line constructions like vehicle and rail roads also serve the overall society and should be protected from any safety and security incidents. 6G ecosystem, with several new technologies and elements, enables several application scenarios to build resilience countermeasures for public safety and critical infrastructure protection as follows.

Safety of Critical and Large-scale Infrastructure

Unauthorized access, spying and damage on critical infrastructure can be fended off with the help of 6G-enabled ISAC. For instance, malicious passive objects, i.e., not emitting in the RF spectrum, pose significant threats to distributed critical infrastructure since they are hard to detect specially in the areas without cameras due to legal regulations or lack of investment. They can be detected by illumination via radio waves within ISAC based on radar sensing principle. Extended over the MNO infrastructure, ISAC-enabled 6G BSs can constitute an airspace monitoring system to provide timely warnings for malicious drones and illegal intruders over the protected critical infrastructure. Therefore, UAVs not participating in some cooperative can also be identified and positions reported by cooperative UAVs can be independently verified. Based on the flight dynamics and the shape of the radar reflection, which may include the micro-Doppler signature, the intention and type of drone or flying object can be identified.

Moreover, relying on a similar ISAC principle, geographically larger facilities such as switchyards, harbors, and cargo centers, can be extensively monitored by NTN elements, e.g., LEO, GEO, and HAPS. In this context, 6G NTN-ISAC system can be considered either as a multi-static radar sensing network, i.e., reusing the transmitted communication signals, or as a distributed radio surveillance network, i.e., monitoring active radio emissions, for target detection with a significant geolocation versatility. Another related application scenario can be tracking and detecting “dark ships” that threaten transportation over seas and violate maritime rules. ISAC over NTN components can help to identify their unintentionally emitting radio signals.

Safety of Public Events

Large public events such as sport competitions and concerts are exposed to a variety of dangers and threats that can harm people and lead to mass panic. For the safety of such events, UAVs can be used for mapping, surveying, inspection, and photography. 6G enables coordinated and real-time communication of UAVs over extended areas, even via direct side links in-between, to interconnect such systems. Furthermore, enabling ISAC over cooperative UAVs as a part of 6G ecosystem can leverage multi-model sensor fusion and diversity gain to localize threats in crowded areas with high precision.

Safety of Highways and Railroads

Long-distance highways contain many distributed parking lots. In such distances, and especially in remote locations, the lack of police presence and limited surveillance measures create safety and security concerns regarding the law enforcement for combating against organized crimes. Enabling ISAC, 6G infrastructure can operate as a networked sensor system to detect malicious radio activity such as non-cooperative communication activities and jammers, and quick detection of passive object by radar sensing. This also serves as a complementary sensory system to the existing video, infrared-, and sound-based threat detection mechanisms.

Similar to enhancing safety and security in long highways, ISAC-enabled 6G systems can allow obstacle and activity monitoring on railroads within risk areas such as crossings, forests, etc., that accidents happen relatively often due to objects, people or animals on the tracks. This monitoring information is then used to inform train drivers or railway control centers in advance for a safe train rerouting and scheduling.

Safety of Private Property

Private homes and properties are threatened by illegal intrusion such as thievery and drone flyovers, as well as occasional damages stem from weather conditions and accidents. 6G-capable devices and routers in a household can constitute an intelligent ISAC subnetwork to detect malicious objects and anomalous changes in the local environment. This could be then used to call emergency and security services for the safety of individuals.

3.7.2 – Resilient Communication for Mission-critical Applications

Critical communication for/among public services and systems over wide area networks should fulfill QoS guarantees even under challenging safety and security incidents like cyber-attacks and large-scale disasters. This includes several layers of proactive and reactive resilience countermeasures that ensure availability, integrity, and security of critical communication. 6G offers broad connectivity via diverse technologies, fosters flexible configurability, and enables state-of-the-art methods to increase security and fault tolerance of critical networks. Some relevant use cases are listed as follows.

Reliable and Standardized Connectivity for Distributed Energy Networks

Transitioning from nuclear and fossil-fuel energy to the renewables, energy systems evolve from centralized entities to decentralized systems with lots of inter-connected producers and consumers over large areas. Their inter-communication includes several control and telemetry channels that demand high data safety and network availability. Currently, the energy service providers build up their own dedicated communication networks to tackle these paradigm changes and missing terrestrial coverage. Employing NTNs, 6G can provide standardized, reliable, and ubiquitous connectivity for large-scale distributed energy systems even in the case of failure of the TN.

Resource Provisioning and Reconfigurability for Mixed-criticality Traffic

Providing guarantees for critical applications in wireless domain is mandatory to have bounded latency with high reliability. Accurate channel estimations, e.g., via radio environment maps (REMs) based on high-resolution (GPS-located) wireless measurements across diverse urban environments, can help UEs and BSs to configure their wireless communication characteristics and measurements to optimize their QoS experience. 6G-enabled systems can perform these reconfigurations by leveraging proactive Radio Resource Management (pRRM). Combining pRRM-enabled reconfigurability and 5G/6G network slicing techniques, safety-critical networks within 6G ecosystem can ensure a reliable resource provisioning for mixed-criticality traffic, e.g., with coexisting hard real-time and best-effort communication requirements.

Quantum-enabled Resilience in 6G

Emerging quantum technologies with enormous computing capabilities render the existing security measures, which rely on the computational complexity of cryptographical functions, penetrable. For instance, the generation of random numbers to harden guessing security keys is only pseudo-random due to the way they are typically generated and can be estimated exploiting quantum computing. This poses a security vulnerability especially for critical networks with several nodes with a large attack space, such as tactile IoT nodes in the context of eMBB communication. Here, 6G will potentially embrace quantum technologies and techniques, such as QRNG to provide true randomness, for security operations over high-connectivity critical networks.

Another benefit of quantum-enabled 6G networks could be reliable time synchronization. The involvement of NTN components makes achieving time synchronization with sub-nanosecond errors very challenging. Here, 6G ecosystem can enable quantum techniques such as Time-Correlated Entangled Photon-based Synchronization (TCEP) based on quantum entanglement, to implement quantum clock synchronization that surpass the precision, reliability, and security of traditional methods such as Precision Time Protocol (PTP). This could be additionally crucial for critical sectors like defense, aerospace, and government.

Resilience and Recovery in Emergency Scenarios

In disasters and emergency scenarios such as earthquakes, wildfires and tsunamis, network services can be disrupted due to infrastructure failures. 6G ecosystem provides a combination of novel technologies for mitigating and recovering from such scenarios. Firstly, employing LAPS, HAPS, and satellites, it can dynamically establish non-terrestrial connectivity to the areas affected by disasters, even in case of failing backhaul connections. Secondly, as one of the promising components in 6G, RIS can reconnect low-reachability or blocked areas, e.g., due to clutter after an earthquake, and improve reliability and stability in wireless channels. RIS-attached drones can also extend the coverage where the BSs collapse. Lastly, satisfying URLLC requirements between critical sensor and robotic components and enabling ISAC, 6G infrastructure can increase the situational awareness of public safety personnel within the tactical bubble in emergency areas.

3.8 – 3D Mobility (3DM)

The transportation systems of the future are expected to entail a higher level of autonomy, flexibility, and safety while transporting people and goods on the ground and in the air. Intelligent transportation on the ground improves traffic and people flow at busy locations, such as major city intersections, parks, and tourist hotspots. UAVs and drones will not only enable fast and efficient logistics and delivery, but also help situational awareness on the roads by establishing an effective aerial observation system. Furthermore, combining environmental observation and sensing capabilities of ground and air vehicles helps achieve a holistic view for coordination of 3D mobility, facilitate dynamic traffic management, reduce congestion, lower fuel consumption, and enhance the overall satisfaction among commuters and passengers. However, this necessitates broad coverage, predictable timing behavior, and reliable communication to ensure the timely delivery of real-time analytics to, from and between vehicles with varying mobility characteristics in both horizontal and vertical dimensions, without compromising the safety and security of essential public services.

Fig. 11: 3D mobility in 6G empowers smart transportation by supporting autonomous vehicles on the ground and in the air, enabling real-time collision avoidance and dynamic traffic management through low-latency communication and integrated sensing.

6G will be a key enabler for a smarter and more resilient urban mobility by delivering critical advancements in reliable and low latency communication and precise coordination between vehicles and infrastructure. A clear novelty in 6G is the introduction of ISAC, which does not exist in current systems, to collect detailed information about the density and movement of people and vehicles, complementing individual vehicle perception.

3.8.1 – Intelligent Ground Transportation

Smart and efficient road traffic emerges as one of the immediate societal priorities to improve passenger safety, energy efficiency, reduce commuting time, and to resolve traffic congestion issues, particularly in cities. To achieve this goal, the intelligent and autonomous transportation systems depend on fast and reliable communication, enhanced sensing with collective perception of the environment, and utilization of edge computational resources on demand to handle large amounts of data processing. These technological requirements are not fully met by the current mobile network standards but they are expected to be supported by 6G regarding the following use cases.

Collaborative Perception in Smart City

Precise detection and monitoring of traffic conditions, vulnerable road user movements and other relevant metrics facilitates better coordination between vehicles and infrastructure in urban environments. This enables smarter traffic light management, optimized routing for public transport, and enhanced safety. The required comprehensive physical awareness in complex city environments can be obtained by collaborative perception and sensing. To achieve this, vehicles can exchange and synchronize positioning meta-data and radar sensing obtained by dedicated automotive radars. Other networked components with sensing capabilities, e.g., ISAC-enabled BSs and UEs, also enrich the overall environmental perception. Expanding into higher frequency ranges, 6G is expected to provide larger bandwidths, enabling radio sensing resolutions to within a single-digit mm-granularity. For instance, sub-THz multi-antenna ISAC systems are expected to be well suited for deployment at street crossings, by providing high data rate access to users (vehicles, vulnerable road users, etc.) when and where needed, while simultaneously performing monitoring to support traffic control.

Vehicular Communication-centric Sensing

Modern cars are using radars in the 26 GHz or 77 GHz band to perceive the environment for driving assistance and autonomous/automated driving functions. Multiple radar antennas for short range, medium range and long range need to be smoothly integrated into the silhouette of the vehicle. As an integral part of 6G, ISAC will enable re-use of the communication antennas, and signal processing in the 6 GHz band to complement and improve the existing vehicular radar sensing. However, radar perception at these lower frequencies is limited by the antenna aperture and the available bandwidth, leading to a lower angular and range resolution of perception. An integrated SAR-based 6G (sidelink) sensing can improve cost efficiency and reduce the required number of antennas within the limited space at a vehicle. SAR improves the spatial sensing resolution by exploiting the motion of the radar to virtually add more antenna elements to the aperture. This helps ground vehicles to localize themselves, monitor nearby semi-static objects, e.g., next to the roadside, and to generate high-resolution maps in real-time even with a 6 GHz communication antenna.

Offloading Automated Driving Functions on the Edge

While the rollout of partially or fully autonomous driving vehicles has begun, computation and data processing for in-vehicle functions are still mostly locally bound. Offloading computation-intensive functions involved in the automated driving software stack to the edge or cloud promises multiple advantages. Firstly, edge and cloud computing paradigms offer an increased computational power than a vehicle itself can sustain. Secondly, centralized offloading servers leverage collective data from multiple traffic participants and enable shared perception and cooperative maneuvers. Lastly, handling fewer functions on-board reduces vehicle power consumption and improves sustainability by yielding an increased driving range. However, offloading functions and sharing relevant data with edge and cloud servers require real-time communication due to the safety-critical nature of highly dynamic road traffic. Here, reliable 6G links enable continuous (edge-) cloud connectivity with low latency and high data rate. Besides, integrating edge computing resources into the 6G ecosystem fosters the development of such dynamic vehicular offloading mechanisms for the near future.

3.8.2 – Traffic Control and Management in Low-Altitude Airspace

As UAVs are increasingly adopted for commercial, logistical, and surveillance applications, the safe and effective coordination of these vehicles in low-altitude airspace presents significant challenges. Existing air traffic infrastructure and uncrewed aircraft systems traffic management (UTM) are not yet equipped to handle the expected volume of UAVs, nor can they fully ensure safety in shared airspace. As a key enabler, 6G technology provides ultra-reliable and low latency communication and integrated sensing capabilities needed to create a cohesive, intelligent airspace traffic ecosystem.

Extended and Autonomous UAV Traffic Coordination

The current limitations in UAV coordination stem from high collision risks and the limited capacity of today's air control systems to handle a substantial increase in air traffic. In order to reduce the take-off weight of the UAVs on the one hand, and to increase the interoperability and coordination capabilities on the other, the flight path simulation for collision anticipation and avoidance is offloaded to ground stations. However, as UAVs move across large areas, coordination must rely on a distributed network of edge computing nodes along their flight paths, rather than a centralized server. 6G communication infrastructure can enable seamless data transfer between drones and the edge, facilitating real-time adjustments in response to environmental conditions, thereby minimizing risks. Additionally, UAVs equipped with 6G device-to-device communication can share data, synchronize movements, and make collaborative decisions in real-time even in scenarios where the coordination from ground is impractical, ensuring agile and autonomous airspace navigation.

Regulatory and Safety Monitoring for Low-Altitude UAV Operations

Beyond collision avoidance, maintaining regulatory compliance and preventing unauthorized use in low-altitude airspace, often termed "U-Space" in Europe, are crucial for safe and organized UAV traffic. The introduction of U-Space aims to regulate commercial drone operations as part of the European Drone Strategy 2.0, yet existing UTM systems fall short in offering robust security and operational safeguards against rule violations or unintended misuse, e.g., by birds, hobby drones, paragliders, etc. Here, 6G's ubiquitous connectivity and ISAC capabilities can bolster airspace regulation by enabling real-time sensing and monitoring over extensive areas. With ISAC, 6G networks can flag rule violations and provide reliable positioning for airborne vehicles, creating a comprehensive safety net within regulated airspace. This establishes a foundation for next-generation air traffic that is both scalable and enforceable, allowing for safe integration of UAVs in public airspace.

4 – Technical Building Blocks

Seven main categories as well as a total of 29 TBBs, which are derived from the UCs within the UCFs, were introduced by the TBB taskforce. The TBBs have been carefully defined in accordance with the TBBs of Hexa-X & -II [11], [12], as well as the provided use cases, and assigned to specific main categories. Table 1 shows the categories as well as the subcategories. The reader is referred to section Appendix A1 for an in-depth description of the UCFs and the corresponding individual use cases.

Table 1: TBB categories and subcategories.

TBB category	ID	TBB subcategory
A: Integrative AI Solutions for Network and Application Enhancement	A1	AI in Infrastructure
	A2	AI in Network Management and Orchestration
	A3	AI in the Service Layer
	A4	AI in Advanced Technologies and Applications
	A5	Digital Twin, Simulation and Data Fusion
B: Comprehensive Network Systems and Services	B1	Network Infrastructure and Technology
	B2	Network Management and Optimization
	B3	Network Types and Configurations
	B4	Cell-free Architecture
	B5	Service Models and Access
	B6	Interfaces for Advanced Technologies and Applications
C: Advanced Network Architectures and Connectivity Solutions	C1	Integrated Network Technologies
	C2	Adaptive Network Infrastructure
	C3	Network Services and Configurations
D: Converged Network Systems and Advanced Communication Technologies	D1	Joint Communications and Sensing
	D2	Sensing, Positioning, and Time Synchronization
	D3	Quantum Technologies for Network Infrastructure
	D4	Interoperability and Service Excellence

E: Integrated Cloud-Edge Ecosystem Transformation	E1	Edge Computing Innovations
	E2	Computing Architectures and Technologies
F: Air Interface	F1	Spectrum
	F1.1	FR1 (410 MHz to 7125 MHz)
	F1.2	FR2 (24.25 GHz to 71.0 GHz)
	F1.3	FR3 (7.125 GHz to 24.25 GHz)
	F1.4	FR THz (92 GHz to 174.8 GHz)
	F1.5	FR THz (>300 GHz)
	F2	Flexible Antenna Structures and Arrays
	F3	Multi-Antenna Beamforming and Beam Management
	F4	Advanced Transceiver Technologies
	F5	Reconfigurable Intelligent Surfaces (RIS)
	F6	Cell-free Massive MIMO
G: Orchestration and Management	G1	Cross-Layer/Cross-Operator Interface for Service Control and Management of Data and Information
	G2	Enabling Interface and Templates for SLA Requests between Network Operators alongside the Technology Deliverable Chain
	G3	Security and Trust

The seven principal categories encompass a range of technologies and solutions, including those pertaining to integrative AI, network and application enhancement, comprehensive network systems and services, advanced network architectures and connectivity solutions, converged network systems and advanced communication technologies, integrated cloud-edge ecosystem transformation, air interface technologies, and orchestration and management. These categories encompass pivotal elements of 6G technologies, including AI-driven network optimization, flexible network architectures, edge computing innovations, and advanced antenna systems for enhanced communication efficiency. An overview of the seven primary categories and their respective subcategories is illustrated in Fig. 12.

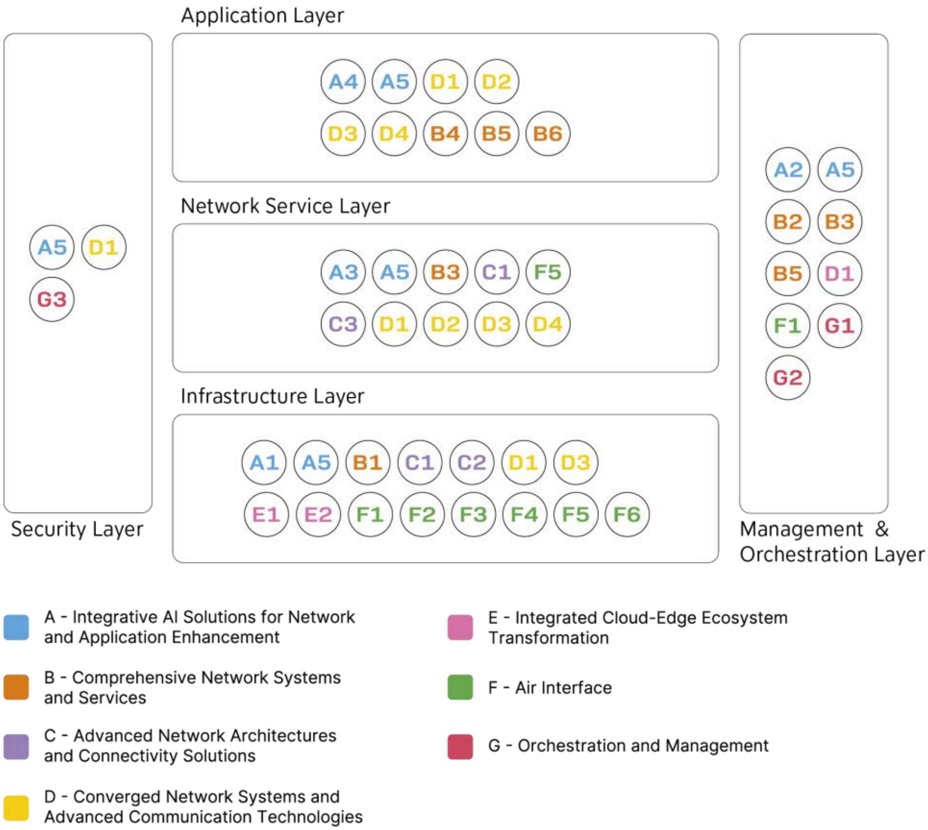

Fig. 12: Overview of the TBB categories and the corresponding subcategories [13].

The figure presents an end-to-end system view of the 6G architecture, categorizing the TBBs across various layers. The Security layer comprises components dedicated to the implementation of security and trust mechanisms. The Management and Orchestration Layer is responsible for the coordination and control of network operations. It employs AI-driven strategies for optimization and automated processes to ensure efficient management across the network. The application layer is concerned with the development of advanced technologies, including XR, as well as other cutting-edge applications. The Network Service Layer provides network services and connectivity solutions, including reconfigurable intelligent surfaces (RIS) and network configurations. The Infrastructure Layer serves as the foundation of the architecture, comprising fundamental infrastructure elements such as spectral and flexible antenna structures, as well as advanced transceiver technologies. The presented architecture outlines a multi-layered network design consisting of three vertical layers: the

Application Layer, the Network Service Layer, and the Infrastructure Layer, each representing distinct functional levels of the network. The Management & Orchestration Layer and the Security Layer span across these vertical layers, providing comprehensive management and security mechanisms. This integration ensures cohesive network management across all layers, thereby maximizing the efficiency and security of the system.

Methodology

The defined TBB categories were shared with the use case authors and they were asked to provide a classification for their corresponding use cases into the categories “Mandatory” (“1”), “Optional” (“0.5”) and “Not Needed” (“0”). Besides, the authors had the opportunity to comment on their choice. In accordance with the defined UCFs, the feedback of the individual use cases was collected and averaged for the UCF to get overall feedback of the UCF in the range of 0 to 1. The results of the individual TBBs are analyzed in the following. In the corresponding figures, the status “Not Needed” is highlighted in yellow, “Optional” in green and “Mandatory” in blue (see example of Fig. 13). The chosen presentation in spider diagrams reflects two levels: the comparison of the three statuses within a UCF and the comparison with all use case families.

Besides, the following points are considered in the analysis of the TBBs: We introduce, based on our expectation, a classification of the TBBs into three development phases of 6G:

- **Phase 1** is defined from now to 2028 and represents the most urgent technologies that need/will be applied from the first release of 6G.
- **Phase 2** corresponds to technologies expected to be standardized between 2028 and 2030.
- **Phase 3** follows from 2030 and includes technologies that will be seen as futuristic and maybe beneficial for later usage but not currently mandatory.

This follows the latest discussions in 3GPP and industry alignments that the first 3GPP 6G specifications are expected on 12/2028, i.e., with the completion of RAN R21 and SA CT specifications. Rel. 22 specifications would follow in mid-2030, and Rel. 23 by approximately the end of 2031.

4.1 – Category A: Integrative AI Solutions for Network and Application Enhancement

Integrative AI solutions for network and application enhancement encompass a range of technologies and strategies specifically relevant to the context of 6G development. These solutions aim to leverage AI to optimize the performance and functionality of 6G networks, services and applications. Integrating AI into various aspects of network, services and application management aims to enhance efficiency, reliability, and overall user experience. The processing may occur at various points within the network, including network functions, management functions, application servers, or even in the UE. It is crucial to enable AI functions to interact and exchange data across these layers to capitalize on ML-generated data and benefit from generative AI capabilities. The layer concept encompasses the following layers: Application Layer, Infrastructure Layer, Security Layer, Management and Orchestration Layer, and Service Layer.

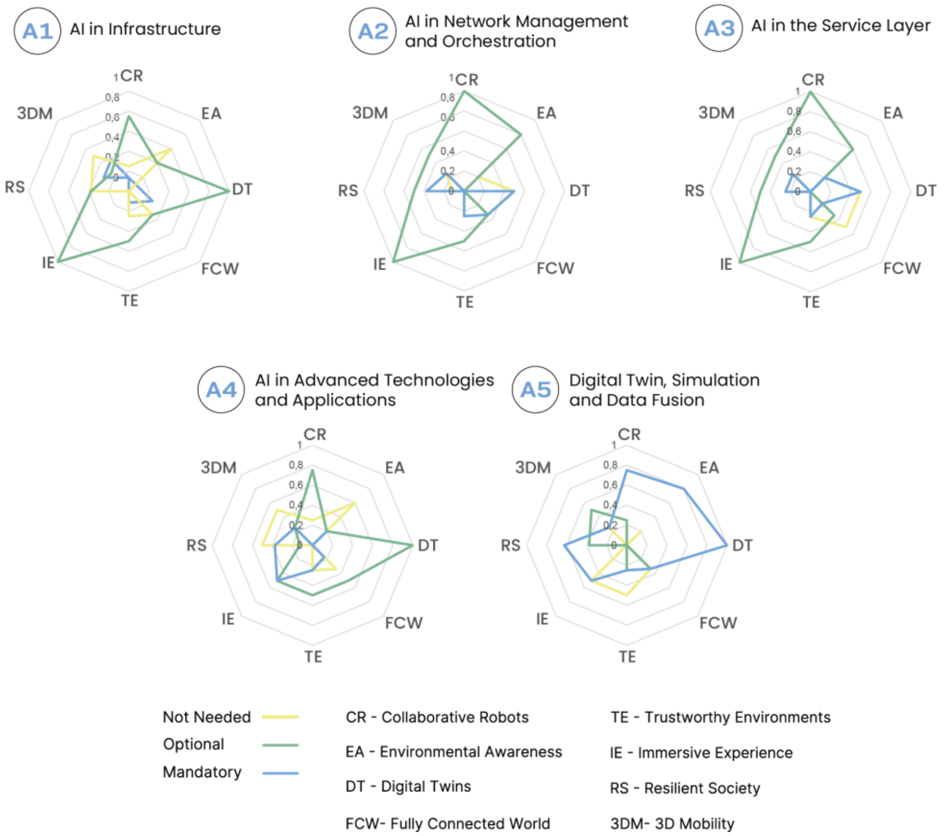

Fig. 13: Need for TBB A (Integrative AI Solutions for Network and Application Enhancement) according to the feedback of the delivered use cases, clustered in the previously mentioned UCFs.

Results

The following figures (starting from Fig. 13) display the analysis results, highlighting the need for the seven UCFs. For an in-depth description of the UCFs and the corresponding individual use cases, the reader is referred to Appendix A.1 - Definition of Technology Building Blocks.

Category A1, corresponding to AI in Infrastructure, shows no significant needs or no needs across all UCFs. Nevertheless, the UCFs *Digital Twin* (*DT*), *Immersive Environment* (*IE*) and *Collaborative Robots* (*CR*) indicate that they see this as an optional category, meaning that their use cases would benefit from A1. Potential benefits also for other UCFs are to organize overlapping nomadic networks (*Fully Connected World* (*FCW*)) or to adjust to the missing communication resources while measuring (*Environmental Awareness* (*EA*)).

Category A2, corresponding to AI in Network Management and Orchestration, shows results similar to those of category A1. The UCFs *CR*, *IE* and *EA* remark on the potential advantage of AI deployed in this layer. Other benefits are to allocate resources in dense (nomadic) network scenarios (*FCW)*, or aspects related to ISAC like Sensing aided communication, resource allocation, processing sensing data (included in several UCFs: *EA*; *3D Mobility (3DM)*; *CR*; *Resilient Society (RS)*). Furthermore, dynamic changes due to human-machine interaction were highlighted to be addressed by category A2.

Category A3, corresponding to AI in the Service Layer, shows a clear advantage for UCFs *CR* and *IE*. Again, aspects related to ISAC in the context of sensing-aided communication and resource allocation were mentioned (included in several UCFs: *EA*, *3DM*, *CR*, *RS*).

Category A4, corresponding to AI in Advanced Technologies and Applications, is especially interesting for UCFs *DT* and *CR*. The other UCFs, however, showed no significant benefit or need regarding this category.

Category A5, corresponding to AI for Digital Twin, Simulation, and Data Fusion, is highly needed for UCFs *DT*, *EA* and *CR*. This category seems to evoke resonance across all UCFs. Only UCF *Trustworthy Environments (TE)* did not highlight great interest.

Summarized, the UCFs *CR*, *IE*, *TE* and *DT* have indicated AI as optional and as a potential need. For instance, in the UCF *CR*, AI aspects related to ISAC would be sensing aided communication, resource allocation, and/or processing sensing data.

A1 (AI in Infrastructure) is assigned to **Phase 3**, as the advanced implementation of AI technologies is critical for optimizing network infrastructure in a fully developed 6G network. A2 (AI in Network Management and Orchestration) falls under **Phase 2**, as integrating AI into network management and orchestration requires substantial deployment and optimization efforts. However, it has to be remarked that fundamental AI/ML capabilities and framework shall be specified from Phase 1 to support Phase 1 UCs which already require AI/ML support. More AI/ML UCs are expected to be introduced also in Phases 2 and 3. A3 (AI in the Service Layer) is categorized as **Phase 2**, since the application of AI to optimize service delivery and resource management in 6G networks necessitates gradual development and refinement. A4 (AI in Advanced Technologies and Applications) is placed in **Phase 3**, as the integration of AI into advanced technologies and applications is vital to achieving full functionality in a mature 6G ecosystem. A5 (Digital Twin, Simulation, and Data Fusion) is positioned in **Phase 1**, as digital twin, simulation, and data fusion technologies, enabled by AI, are seen mandatory for the current research and development. The classification is summarized in Table 2.

Table 2: Classification of Category A (Integrative AI Solutions for Network and Application Enhancement) into three Phases of 6G.

Category	Phase 1	Phase 2	Phase 3
A1			
A2			
A3			
A4			
A5			

A1: AI in Infrastructure
A2: AI in Network Management and Orchestration
A3: AI in the Service Layer
A4: AI in Advanced Technologies and Applications
A5: Digital Twin, Simulation, and Data Fusion

4.2 – Category B: Comprehensive Network Systems and Services

The TBB "Comprehensive Network Systems and Services" highlights developments in network technology that aim for a modular and service-oriented architecture composed of physical elements and (software microservice-) functions. This architecture is intended to enhance the adaptability and scalability of network services by prioritizing further softwareization. By implementing flexible orchestration and dynamic placement of network functions virtualized within a cloud continuum, 6G meets low latency and high-reliability demands. This software-driven approach enables the deployment of functions and services on demand, forming the basis for the continuous evolution of network systems rather than relying on iterative technological revolutions. This modular structure, supported by further softwareization, enables more specific and demanding applications and services, making 6G a key technology for future communication requirements.

Results

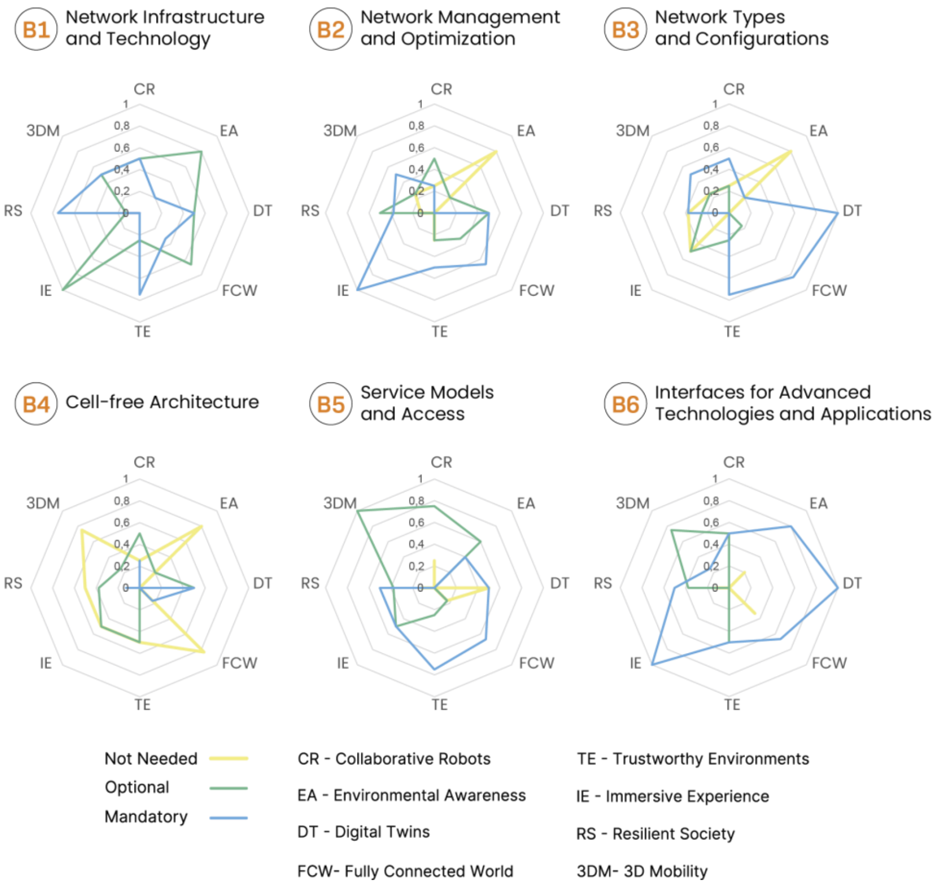

Fig. 14: Need for TBB B (Comprehensive Network Systems and Services) according to the feedback of the delivered use cases, clustered in the previously mentioned UCFs.

Evaluating the global feedback for category B, shown in Fig. 14, there is a clear need for comprehensive network systems and services for UCFs *TE* and *DT*. The *3DM* UCF highlights an optional need. If the sub-categories are revisited, there are even more knowledgeable differences.

Category B1, corresponding to network infrastructure and technology, is considered mandatory for the UCFs *TE* or *RS*. Overall, the other UCFs and especially the UCF *IE* also highlight that the TBB B1 will be beneficial. In several UCFs, it was mentioned that as there is currently not a clear decision on how ICAS will be implemented in 6G, it might require tailoring the radio head of the RAN infrastructure to support ICAS functionalities.

Category B2 corresponds to network management and optimization. The UCFs *DT* and *FCW* stand out, with a high proportion of direct demands and strong interest in and benefits of this TBB. In parallel, the UCF *IE* highlights its need and *CR* and *RS* its optional benefits. At the same time, UCF *EA* has less need.

UCF F*CW* states that they need to create a comprehensive network containing terrestrial, aerial, and space components, especially in organic 6G deployment. Besides, network management is mandatory for UCF *DT* as it can change according to requirements.

Category B3 relates to network types and configuration. The UCFs *TE*, *DT*, and *FCW* indicate that this TBB is totally, or at least, to a great extent, mandatory for the UCF, respectively. UCFs *EA* and, less significantly, *IE* remark that this TBB is not seen as needed. In the context of category B3, the resource allocation of multiple NPNs was named by *FCW*. Furthermore, it is remarked that an underlayer network in a network of networks manner is highly needed and that the mentioned aspects regarding creating a comprehensive network are still applicable.

Category B4 considers a cell-free architecture. Except for UCF *CR*, most UCFs see no particular need in this category, notably the UCFs *EA*, *FCW*, or *3DM*. However, UCF *EA* states an optional need in the case of bi-static ICAS operations, while at the same time, it is remarked that ICAS should not be dependent on the architecture - cell or cell-free but should support both. As a result, ICAS can benefit from cell-free architecture. Furthermore, UCF *DT* sees TBB B4 as mandatory in the context of human-machine interaction or in device-to-device scenarios in general.

Category B5 corresponds to service models and access. A clear need for or at least a foreseen benefit of this TBB is recognizable overall in all UCFs. The UCF *TE* is outstanding with a high need, and the UCF *FCW* has a need greater than 0.65. *3DM* does not see the TBB as mandatory in the first place; however, it recognizes a substantial benefit for their corresponding use cases. In the UCF *EA*, the need for the B5 category arises because of the necessity of an NTN-based operation. Still creating a comprehensive network, and the need for the UCF *FCW* is stated. UCF *CR* adds that Sensing-as-a-Service needs to be considered as a unique and different service model from the traditional network connectivity service. The sensing will have different QoS definitions, but the achievable QoS of sensing needs to be considered.

Category B6 relates to interfaces for advanced technologies and applications. Most UCFs mark this TBB as mandatory, except for *3DM*, which indicates benefits from the TBB. Several UCFs (i.e., *CR* and *DT*) state that B6 will be very useful for exposed interfaces. Besides, it is stated that there is a need, e.g., for ICAS API to be exposed to provide the sensing function.

To summarize, category B and its subcategories were seen as mandatory or beneficial for every UCF. Only subcategory B4, corresponding to cell-free architecture, did not receive a high resonance.

Table 3: Classification of Category B (Comprehensive Network Systems and Services) into three Phases of 6G.

Category	Phase 1	Phase 2	Phase 3
B1			
B2			
B3			
B4			
B5			
B6			

B1: Network Infrastructure and Technology
B2: Network Management and Optimization
B3: Network Types and Configurations
B4: Cell-free Architecture
B5: Service Models and Access
B6: Interfaces for Advanced Technologies and Applications

The classification in the three phases of 6G is shown in Table 3. B1 (Network Infrastructure and Technology) is assigned to **Phase 1**, as foundational elements like network virtualization and modularity are expected to be developed and available early. B2 (Network Management and Optimization) also falls under **Phase 1**, as flexible orchestration and continuous optimization are essential initial functions in 6G deployment. B3 (Network Types and Configurations) is categorized in **Phase 1**, as technologies for flexible network configurations, particularly for device-to-device communication, are foundational for early 6G functionality. B4 (Cell-free Architecture) is assigned to **Phase 3**, as this advanced network architecture will play a key role in fully mature 6G systems by enabling distributed and device-to-device communication. B5 (Service Models and Access) falls within **Phase 1**, with unified subscription standards and tailored QoS requirements anticipated to be fundamental from the outset. Finally, B6 (Interfaces for Advanced Technologies and Applications) is also in **Phase 1**, as network-centric functions and APIs for advanced 6G services are expected to be initially researched and deployed to support emerging applications.

4.3 – Category C: Advanced Network Architectures and Connectivity Solutions

Advanced Network Architectures and Connectivity encompass all technologies that aim to provide a flexible network architecture and seamless interoperation between different networks. This includes the joint operation of terrestrial, non-terrestrial, and various terrestrial NPNs like 5G, non-3GPP or Nomadic Networks. The high flexibility of the infrastructure enables dynamic network adaptation to changing conditions and supports advanced network services like Network Slicing.

<u>Results</u>

The TBB category of advanced network architectures and connectivity solutions is diverse, like depicted in Fig. 15. UCFs like *TE* and *FCW* indicate this TBB section to be mandatory, whereas UCF *EA* concludes to have no need. However, considering all aspects, a comprehensive analysis of the subcategories clarifies the need/no need or benefits that the UCFs state.

Category C1 relates to integrated network technologies. UCF *TE* stands out, next to UCFs *3DM* and *FCW*, and reports a mandatory character of the TBB. UCF *DT* classifies the TBB as highly beneficial for the corresponding use cases, particularly in device-to-device scenarios, e.g., with a wireless backhaul in industrial campus networks. UCFs *EA* and *IE* show even contradictory results between mandatory and no need, while UCF *EA* states the need due to the necessity of an NTN-based operation.

Category C2, corresponding to adaptive network infrastructure, is considered mandatory for UCFs *TE* or *FCW*. Again, UCF *EA* concludes to have no need. The other UCFs show no clear trend towards the three options (mandatory, beneficial or no need). However, UCF *DT* provides a clear indication of the need for adaptive network infrastructure, particularly in the context of automatic restructuring of the network, which should reassure and instill confidence in the decision-making process.

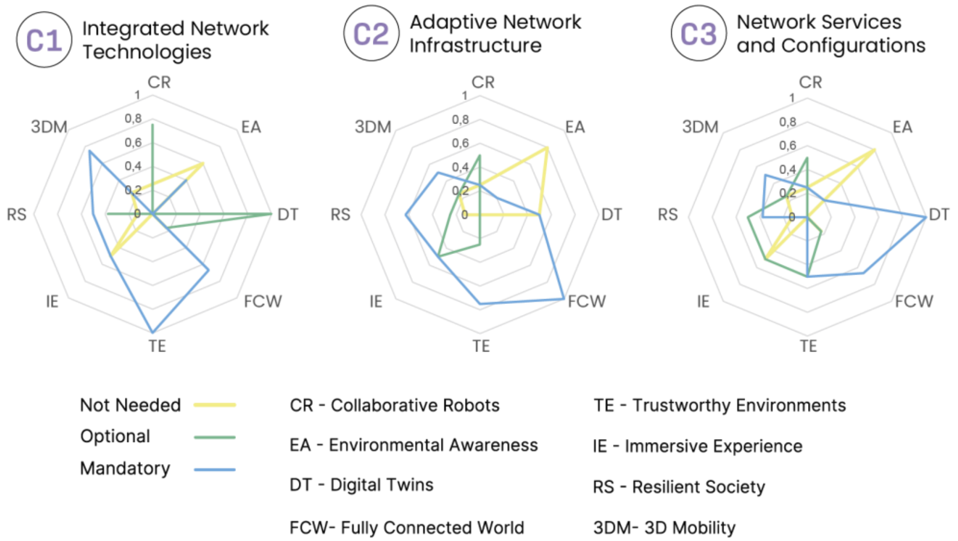

Fig. 15: Need for TBB C (Comprehensive Network Systems and Services) according to the feedback of the delivered use cases, clustered in the previously mentioned UCFs.

Category C3 considers network services and configurations within the advanced network architectures and connectivity category. UCFs *DT*, *TE*, and *FCW* mark their need, whereas UCF *EA*, like the other C categories, states no need. The UCF *RS*, however, indicates a benefit and need of this subcategory. Within the UCF *DT*, the mandatory aspect is argued in the context of individual services for various UCs.

To summarize, category C and its subcategories were considered mandatory or beneficial for most UCFs, except for UCF *EA*. The high needs for the whole category, including C1 (Integrated Network Technologies), C2 (Adaptive Network Infrastructure) and C3 (Network Services Configurations), along nearly all UCFs illustrate the great demand. In consequence, the categorization to **Phase 1** (see Table 4) and with that the highest priority is foreseen. Especially, as adaptable and flexible networks are foreseen in many 6G visions and research works, which enables bringing together usage of technologies along NPNs, public networks as well as NTNs and TNs.

Table 4: Classification of Category C (Comprehensive Network Systems and Services) into three Phases of 6G.

Category	Phase 1	Phase 2	Phase 3
C1			
C2			
C3			

C1: Integrated Network Technologies
C2: Adaptive Network Infrastructure
C3: Network Services and Configurations

4.4 – Category D: Converged Network Systems and Advanced Communication Technologies

Converged Network Systems and Advanced Communication Technologies concentrate on beyond-communication functionalities that will appear in the context of 6G. These follow from the recent technological advancement towards:

- Higher frequencies and larger bandwidths.
- Integration of intrinsic computational capabilities within the network.
- Quantum technologies.

As a result, a 6G system converges towards and merges with previously separated technologies, most prominently Radar sensing with JCAS. These technological advances also include capabilities that facilitate the application-driven adjustment of the network to provide service excellence. Four subcategories are defined.

<u>Results</u>

The analysis of the needs assessment, summarized in Fig. 16, indicates that there is only a slight mandatory need for Category D in the UCFs of *EA*, *DT*, *TE*, and *RS*. Additionally, there is an optional need in the areas of UCFs *DT* and *TE*. In contrast, it was found that there is no need for the UCFs *FCW* and *IE*.

Category D1 relates to Joint Communications and Sensing (JCAS), also known as ISAC, encompasses technologies that utilize telecommunication infrastructure for radio sensing the environment, involving detection, separation, and classification in addition to estimation. Beyond traditional radar like systems with transmitter and receiver functionalities, ISAC also covers techniques where a receiver alone detects radio emissions from surrounding objects. The analysis of the diagram indicates that there is a strong mandatory requirement for the UCF *EA*, while there is a medium mandatory requirement for UCF *RS*. Additionally, there is potential for UCFs *CR*, *3DM*, and *TE* to benefit from ISAC. In contrast, there is no need for UCFs *IE* and *FCW*.

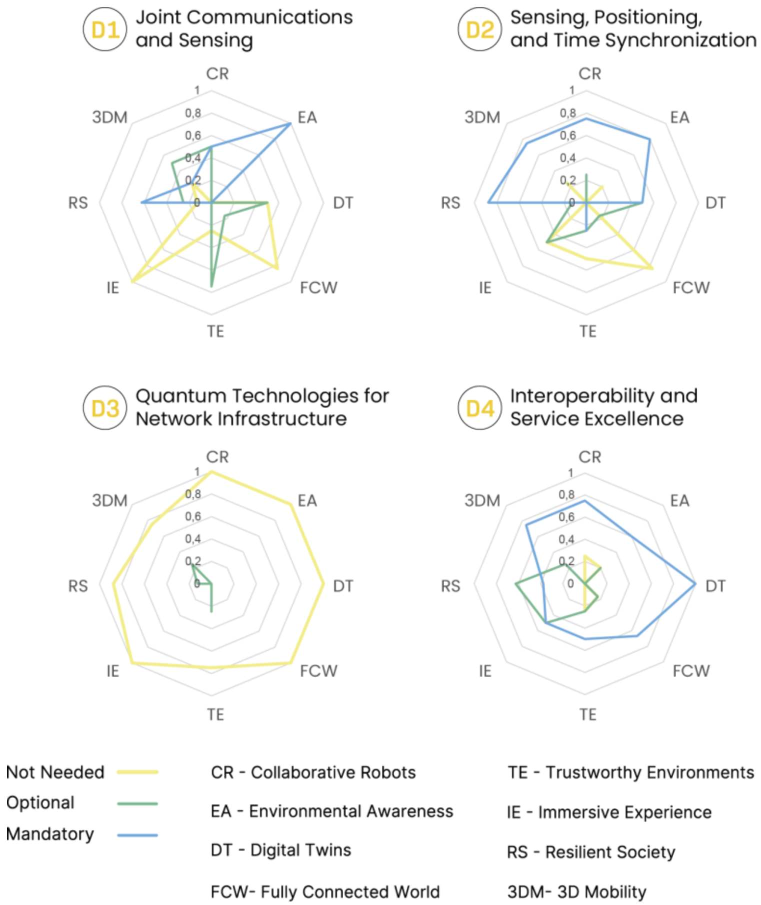

Fig. 16: Need for TBB D (Converged Network Systems and Advanced Communication Technologies) according to the feedback of the delivered use cases, clustered in the previously mentioned UCFs.

Category D2, corresponding to Sensing, Positioning, and Time Synchronization, encompasses technologies for localizing cooperative objects within the network through estimation and for distributing and acquiring spatial and temporal information via time synchronization. The key difference between this category and D1 is that JCAS focuses on sensing non-cooperative objects, while this Category involves sensing and positioning of active, cooperative objects, which are designed to work with the infrastructure. The analysis of the diagram indicates an urgent need for UCFs *EA*, *CR*, *3DM*, and *RS*. In contrast, there is no need for UCF *FCW*.

Category D3 considers Quantum Technologies for Network Infrastructure and encompasses all quantum-based technologies supporting specific aspects of the network, such as highly accurate clock synchronization using quantum entanglement or QKD for secure communications. The analysis of the diagram indicates that there is no general need for Quantum Technologies for Network Infrastructure, especially in the UCFs *FCW*, *DT*, *EA*, *CR*, and *IE*. However, it should be noted that these technologies may become mandatory in the future as the field evolves, such as for UCFs *TE, 3DM*, and *RS,* which identify benefits.

Category D4 refers to Interoperability and Service Excellence. This TBB encompasses all technologies aimed at managing and balancing the different requirements of UEs on the network within an area, including potentially heterogeneous tasks based on individual applications, such as data for XR, JCAS/ISAC, V2X, etc. The analysis of the diagram indicates a high mandatory requirement for UCFs *DT*, *CR*, and *TE*. These categories demand extensive interoperability and exceptional service quality, isolation, to effectively support their specific applications. Additionally, there is a high optional requirement for UCF *RS*. This suggests that technologies for interoperability and service excellence can significantly contribute to societal resilience by ensuring that networks operate robustly and reliably. It is also important to note that these technologies might become relevant if the Search and Rescue operation needs to be balanced against data transmissions in the network.

D1 (JCAS) is classified in **Phase 2**, as integrating communication with the aim using the telecommunication infrastructure in parallel for radio sensing of the environment necessitates substantial deployment and optimization endeavors. Radio sensing covers both radar-sensing and spectral sensing. D2 (Sensing, Positioning, and Time Synchronization) is situated within **Phase 1**, where sophisticated network functionalities such as precise positioning and time synchronization become indispensable for applications like SLAM and XR within a fully developed 6G network. D3 (Quantum Technologies for Network Infrastructure) is situated within **Phase 3**, as quantum-based synchronization and secure communication are fundamental and thus not prioritized for early 6G research and development. Lastly, D4 (Interoperability and Service Excellence) is situated within **Phase 1**, as it focuses on achieving high service quality and interoperability through complex functionalities like network slicing and computational offloading, which are best suited for a mature 6G ecosystem. An overview of the discussed classification is given in Table 5.

Table 5: Classification of Category D (Converged Network Systems and Advanced Communication Technologies) into three Phases of 6G.

Category	Phase 1	Phase 2	Phase 3
D1			
D2			
D3			
D4			

D1: Joint Communications and Sensing
D2: Sensing, Positioning, and Time Synchronization
D3: Quantum Technologies for Network Infrastructure
D4: Interoperability and Service Excellence

4.5 – Category E: Integrated Cloud-Edge Ecosystem Transformation

Category E deals with the transformation of the integrated cloud-edge ecosystem, encompassing the integration of edge, cloud, and fog computing to optimize data processing, storage techniques, and computing architectures. These technologies are crucial for the development of 6G networks, as they aim to enhance efficiency, reliability, and user experience. Edge computing processes and stores data directly close to the source, thereby reducing latency and improving real-time capabilities. Fog computing complements this by introducing an intermediate layer between edge devices and the central cloud, facilitating optimized data management and more efficient resource utilization. Edge computing architectures include edge devices, edge computing nodes, and central cloud infrastructures, which are responsible for decentralized data processing. Orchestration and robust network connectivity ensure efficient resource utilization and seamless interaction between local processing and the central cloud. The layer concept encompasses the same layers as described above.

<u>Results</u>

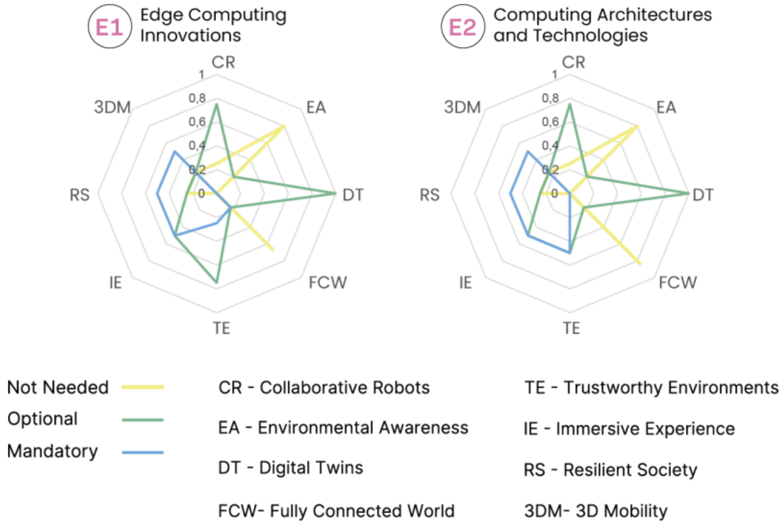

Fig. 17: Need for TBB E (Integrated Cloud-Edge Ecosystem Transformation) according to the feedback of the delivered use cases, clustered in the previously mentioned UCFs.

The TBB category of integrated cloud-edge ecosystem transformation is stating for most UCFs only an optional demand or even no need, shown in Fig. 17. The individual analysis of the subcategories is provided below.

Category E1, relating to Edge computing innovation, encompasses all technologies which enable the processing and storage of data closer to the application or data source. The UCFs *TE*, *DT* and *CR* stand out due to the analysis indicating a high potential benefit of these UCFs. The category *DT* indicates that the TBB could be highly beneficial for device-to-device scenarios, particularly in digital twin applications, where real-time data processing is crucial, often involving the calculation of images from the data. In contrast, the UCFs *EA* and *FCW* show no need for edge computing innovation, whereas UCFs *RS*, *3DM* and *IE* see edge computing to a (large) extent as mandatory.

Category E2 corresponds to Computing Architectures and Technologies and encompasses a decentralized framework designed to process data and execute applications closer to the source of data generation. The analysis indicates that there is a high potential benefit for the UCFs *DT* and *CR*. In contrast, there is no need of this technological building block for the UCFs *EA* and *FCW,* whereas again UCFs *RS, 3DM, IE* and *TE* see this TBB as (only slightly) necessary.

To summarize, most UCFs view the computing architectures and technologies as optional or unnecessary and do not explicitly see this as a mandatory step forward, except for the results for UCFs *3DM*, *RS*, and *IE*, which report a medium mandatory need. The classification in the three phases of 6G is indicated in Table 6 and discussed in the following:

E1 (Edge Computing Innovation) is categorized in **Phase 2**, as the computing capacities across the entire network as well as the various types of offloading necessitate gradual development and refinement. The same applies to E2 (Computing Architectures and Technologies), which is also categorized to happen in **Phase 2**, as the decentralized framework to process data and execute applications closer to the source of data generation are still under development.

Table 6: Classification of Category E (Integrated Cloud-Edge Ecosystem Transformation into three Phases of 6G.

Category	Phase 1	Phase 2	Phase 3
E1			
E2			

E1: Edge Computing Innovations
E2: Computing Architectures and Technologies

4.6 – Category F: Air Interface

This TBB category, which summarizes all TBBs closely linked to the physical and MAC layer and, therefore, to the hardware used, underscores the necessity of intelligent antenna systems and transceiver architectures. These are not just recommended, but mandatory for future (fully) integrated JCAS/ISAC systems. Subcategories representing the TBBs from the collected use cases are defined below.

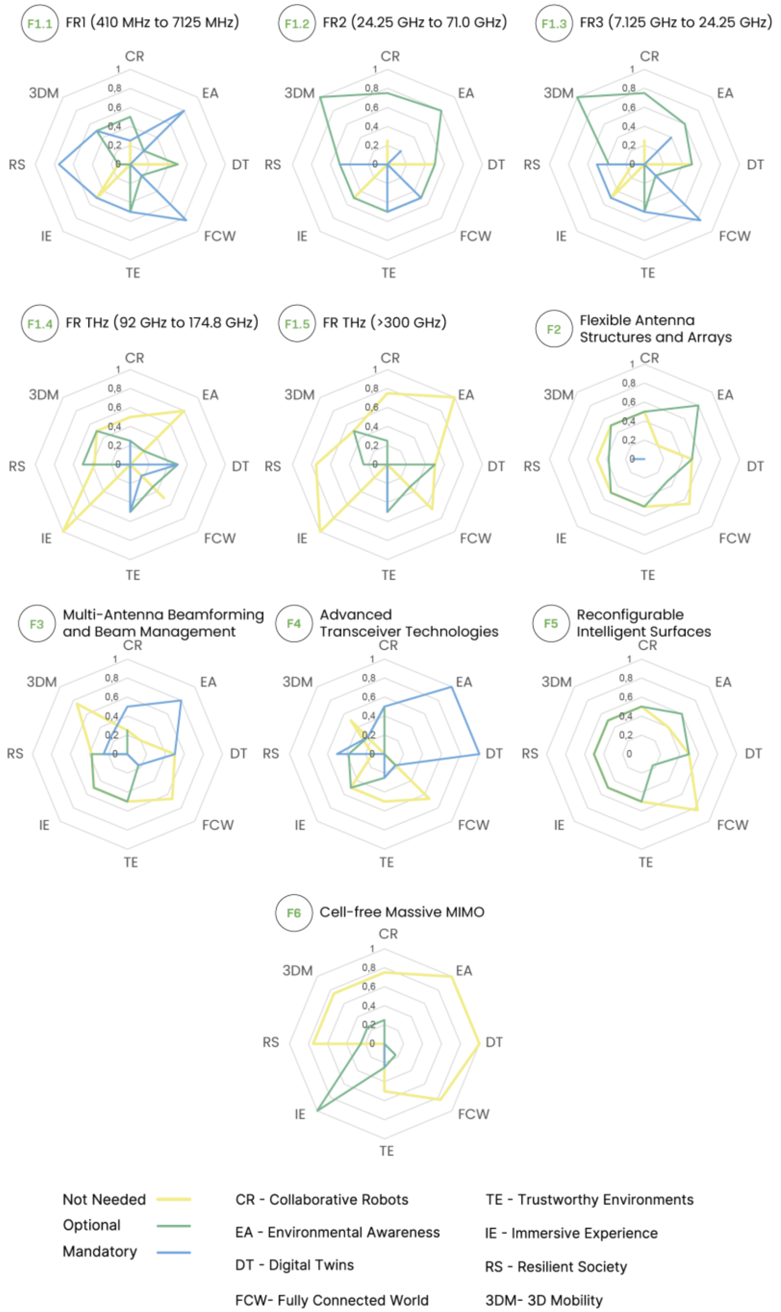

Fig. 18: Need for TBB F (Air Interface) according to the feedback of the delivered use cases, clustered in the previously mentioned UCFs.

Results

As Fig. 18 indicates, the TBB category of air interface is diverse. Therefore, an analysis of the subcategories has to clarify the need/no need or benefits for the seven UCFs.

Category F1 and, most likely, the corresponding subcategories *F1.1* to *F1.5* reflect UCFs' perspectives on the considered frequency bands, starting from the FR1 band of 410 MHz to 7125 MHz and ending with the THz-band over 300 GHz. The FR1 band is mandatory for most of the UCFs (explicitly naming *FCW*, *RS*, *EA*, *3DM*, and *TE*); only *DT* and *IE* seem not to have a clear vision of this. In the FR2 band, however, the mandatory character changes to an optional benefit, remarking the expectations of *DT* and *IE*, which state a significant lack of need in this band. The FR3 band shows an almost identical picture to the FR2 band, slightly shifting from beneficial to mandatory for *FCW*, *IE*, and *EA* UCFs. Entering the THz-frequency bands (below 175 GHz), the majority of the UCFs do not state a need, except for the *TE* and *DT* UCFs. This is increased when moving to above 300 GHz, where all UCFs, again except *TE*, are said to see no need for their corresponding use cases or only a slight benefit. In the context of ICAS, the need for bandwidth is raised across several UCFs as the given spectrum influences the sensing resolution; however, for higher carrier frequencies (above 150 GHz), the required antenna output power might not be available. That is why there is a concern that high frequencies may limit the range and coverage requirements of mobile robotics (UCF *CR*). However, speaking about fully integrated applications, usable frequency bands will be limited to the available bands provided by the communication network deployment.

Category F2, considering flexible antenna structures and arrays, shows only an optional character for UCF *EA*. There is clearly no need for the other UCFs, and/or only a minor benefit is seen.

Category F3 relates to a TBB linked to multi-antenna beamforming and beam management. UCFs *3DM* and *FCW* indicate no need, whereas the *EA* and *CR* see it as mandatory. UCF *DT* split into mandatory and no need, explaining the need by referring to the necessity to overcome high losses in D-band and to guarantee stable transmission even in static scenarios. UCF *TE* highlights the benefits of this TBB. UCF *EA* states a mandatory character and indicates this exemplarily in regard to SAR applications, which need only one beam (preferably narrow) along a specific path (linear or circular); however, other beams are required for communications.

Category F4 corresponds to advanced transceiver technologies. The UCFs *EA*, *DT*, *RS* and *CR* indicate that this subcategory is mandatory for their corresponding use cases. On the other hand, *3DM*, *TE* and *FCW* conclude that there is mostly no need. *DT* states that D-band transceiver architectures are needed.

Category F5 considers reconfigurable intelligent surfaces. All UCFs do not see a mandatory character of this TBB; however, most of them see such surfaces as beneficial, most notably UCF *EA*. The *CR* UCF, for example, named better coverage and connectivity. *DT* also stated the relevance of networked applications in manufacturing. *FCW* stands out, indicating a clear "no need" statement.

Category F6, corresponding to cell-free massive MIMO, is seen by most UCFs (*EA*, *DT*, *FCW*, *CR*, *3DM* and *RS*) as uncritical. UCF *IE*, on the other hand, marks it as beneficial, and UCF *TE* is indecisive.

Table 7: Classification of Category F (Air Interface) into three Phases of 6G.

Category	Phase 1	Phase 2	Phase 3
F1.1			
F1.2			
F1.3			
F1.4			
F1.5			
F2			
F3			
F4			
F5			
F6			

F1: Spectrum
F1.1: FR1 (410 MHz to 7125 MHz)
F1.2: FR2 (24.25 GHz to 71.0 GHz)
F1.3: FR3 (7.125 GHz to 24.25 GHz)
F1.4: FR THz (92 GHz to 174.8 GHz)
F1.5: FR THz (>300 GHz)
F2: Flexible Antenna Structures and Arrays
F3: Multi-Antenna Beamforming and Beam Management
F4: Advanced Transceiver Technologies
F5: Reconfigurable Intelligent Surfaces
F6: Cell-free Massive MIMO

Except for the results shown in the context of the used frequency bands, the overall results show that most UCFs do not explicitly mention the air interface as a critical TBB. The classification in the three phases of 6G is indicated in Table 7 and discussed in the following:

F1 (Spectrum) is categorized depending on the frequency bands in various phases. FR1 and FR3 (TBB F1.1 and TBB F1.3) belong to **Phase 1**, while FR2 is categorized in **Phase 2** and frequencies in the THz range (TBB F1.4 and F1.5) in **Phase 3**. F2 (Flexible Antenna Structures and Arrays) belongs to **Phase 3**, as the need in terms of flexible structures and flexibility about the spectrum is currently seen with less need. The topic is still in the research and development stage. F3 (Multi-Antenna Beamforming and Beam Management) is assigned to **Phase 2**, as the need for novel beam management (e.g., AI-controlled beam management) is increasing. F4 (Advanced Transceiver Technologies) is part of **Phase 1** ensuring the need of the transceiver parts after the physical antenna and a potential beamforming structure according to the increase in carrier frequencies and bandwidths. F5 (Reconfigurable Intelligent Surfaces) as well as F6 (Cell-free massive MIMO) are classified to **Phase 3**, as both technologies seem to be in the early stages of development and research, without a clear industrial use case.

4.7 – Category G: Orchestration and Management

Orchestration and management represent a fundamental building block of 6G's end to end system architecture. They enable automated configuration of services and networks and the closed-loop monitoring of Service Level Agreements (SLA) of end users' services, necessary to manage these resources effectively. The orchestration and management capabilities will enable the specific deployment of services to users or groups of users and the creation of "network slices" across the technical delivery chain of multiple operators' technical domains, from user A to user B or a server of an application.

<u>Results</u>

The analysis of the diagrams, provided in Fig. 19, indicates a medium mandatory requirement across all use case fields. This means that most application areas benefit from robust orchestration and effective management to meet performance requirements. Additionally, there is an increased optional need for UCF *IE*. This can be explained by the maximum optional requirement for the specific subcategories G1 and G2. G1 refers to the Cross-Layer/Cross-Operator Interface for Service Control and Management Data and Information, while G2 encompasses Enabling Interface and Templates for SLA Requests between Network Operators alongside the Technology Deliverable Chain. This increased demand highlights the importance of orchestration and management in supporting complex and data-intensive applications such as Immersive Experiences.

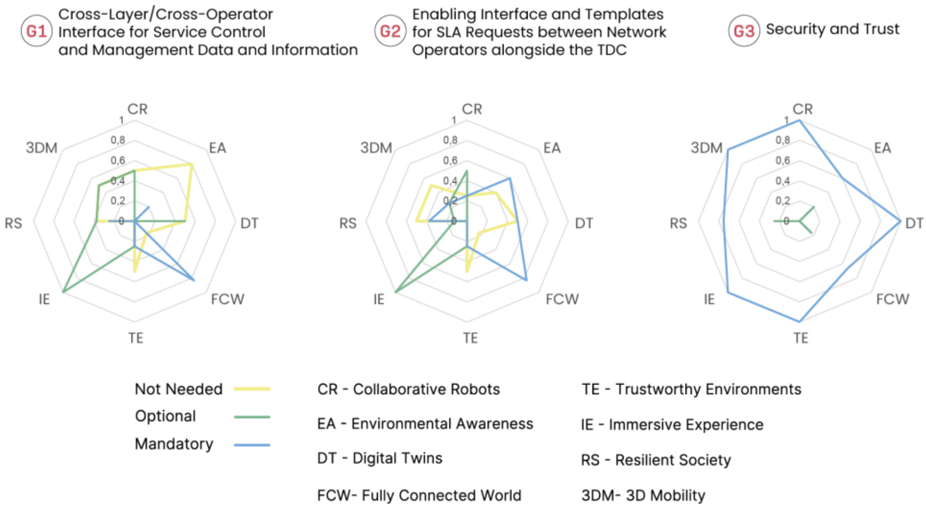

Fig. 19: Need for TBB G (Orchestration and Management) according to the feedback of the delivered use cases, clustered in the previously mentioned UCFs.

Category G1 relates to Cross-Layer/Cross-Operator Interface for Service Control and Management of Data and Information. In the modern telecommunications sector, network operators must extensively manage their network elements, including configuration and monitoring, to ensure specific SLAs. A recent analysis by 6G-LEGO emphasized the relevance of Network Slices and suggested that network operators exchange information on SLA templates and facilitate the activation of private Slices/SLAs on demand [14], [15] – current quality on demand API of GSMA Open Gateway. The analysis of the diagram indicates a high mandatory requirement for UCF *FCW*. This means that interfaces for service control and management of data and information are crucial in fully connected worlds to ensure efficiency and reliability. In order to allow, e.g., Content Delivery Networks CDNs with defined SLAs controlled from within the applications (and negotiated between the networks), these interfaces must be highly adaptable. Additionally, there is a maximum optional requirement for UCF *IE*. This demand indicates that immersive applications, such as VR and AR, could greatly benefit from the capabilities of G1 interfaces to provide seamless and high-performance user experiences. Being interoperable with such kind of interface could be highly relevant, especially in environments where seamless integration is necessary. In contrast, there is no need for UCFs *EA*, *CR*, and *3DM*. These categories require less support from G1 technologies, as their service control and data management needs are less complex or less critical.

Category G2 corresponds to Enabling Interface and Templates for SLA Requests between Network Operators alongside the Technology Deliverable Chain. In the 5G context, the Network Exposure Function (NEF) serves as an interface between network infrastructure and external entities, enabling authorized third-party applications to securely access network services. The NEF functions as a module requesting specific capabilities from operators' core network control, with SLAs precisely defined using slice templates. Research is recommended into interfaces for exchanging SLA templates between operators to enable automated transactions. SLA templates should include 6G attributes, particularly for applications like 3D gaming and AR/VR. The analysis of the diagram indicates a highly mandatory need for UCF *FCW*, similar to G1. Additionally, there is a maximum optional requirement for UCF *IE*. In contrast, there is no need for UCFs *EA*, *CR*, and *3DM*.

Category G3 refers to Security and Trust. The forthcoming 6G networks will be equipped with security and trust capabilities that can be accessed on demand. These capabilities will be available to end users, applications, and operators via APIs. 6G networks will include a security layer analogous to the data layer, providing security services to end users, and applications (securing brown field applications as well) while automatically optimizing security policies and functions from the network function layer to the resource layer of the underlying infrastructure. The analysis of the diagram indicates a maximum mandatory need for UCFs *DT*, *CR*, *3DM*, *IE*, and *TE*, as well as a generally high mandatory requirement across all UCFs. These demands highlight the importance of comprehensive security and trust solutions to support complex and critical applications in 6G networks.

The classification in the three phases of 6G is indicated in Table 8. G1 (Cross-Layer/Cross-Operator Interface for Service Control and Management Data and Information) is classified in **Phase 3**, as cross-operator orchestration and management of SLAs entail a high degree of complexity and the integration of futuristic applications. This technology, which facilitates the seamless exchange and activation of private slices and SLAs across multiple operators, will become essential only in an advanced 6G ecosystem, where multi-operator collaboration is anticipated to reach full maturity. G2 (Enabling Interface and Templates for SLA Requests between

Network Operators) is classified in **Phase 2**, as the establishment of standardized SLA templates and interfaces among network operators necessitates a moderate level of development and coordination efforts to enable efficient, automated transactions for SLA handling. This is of critical importance for the purpose of bridging the demands of both public and non-public networks in the context of 6G, and for enabling the dynamic allocation of network resources at the earliest stages of advanced 6G. G3 (Security and Trust) is situated within **Phase 1**, as the establishment of foundational security features, including the incorporation of a dedicated security plane, the development of trust infrastructures, and the integration of on-demand security capabilities, is of paramount importance for the creation of a resilient and secure 6G network from its inaugural implementation.

Table 8: Classification of Category G (Orchestration and Management) into three Phases of 6G.

Category	Phase 1	Phase 2	Phase 3
G1			
G2			
G3			

G1: Cross-Layer/Cross-Operator Interface for Service Control and Management of Data and Information
G2: Enabling Interface and Templates for SLA Requests between Network Operators alongside the Technology Deliverable Chain
G3: Security and Trust

5 – Features and Requirements

The following chapter provides an overview of the current status and findings on 6G features from the German 6G program. In this section, we consider any characteristic that 6G should offer to enable use cases beyond the current level of technology a "6G feature". In comparison to the Technical Building Blocks above, the features refer to user-centric demands, while the TBBs provide the technological means to fulfill these. To show the demands and also enable the potential of frequently mentioned features, we map the features to the UCFs introduced and described in 3 – Use Cases. On the one hand, this deepens the understanding of the UCFs by providing more context on the technical challenges raised. On the other hand, it deepens the understanding of the features, showing why certain features are essential, and under what circumstances.

Methodology

To receive use case-specific insights, we initiated a survey among the use case authors who had contributed to the working group. We extracted content from the requirements sections of all 78 use cases and aligned their terminology. After refining the remaining requirements, 61 clearly defined features remained. The survey covered all these features with questions about their necessity for a respective use case, providing feature definitions to ensure a common understanding among all survey participants. Use case authors were requested to name their use case to map their statements on the features to a specific use case and, following the use case aggregations from the harmonization task force, to a UCF. Some of the questions in the survey only asked for a yes/no answer. Such a question could be, "Is cloud computing an important aspect of your use case?" Other questions asked for a more detailed answer, e.g., regarding timing behavior, targeted metrics with formulations like "Yes, the allowed mean transmission time is XX with a max deviation of YY" or "Is transmission time an important aspect for your use case?".

The presented findings reflect a snapshot of the BMBF 6G projects actively participating in the working group as of July 2024. Thus, they are not to be considered final results but rather as developments visible to the working group at an early stage. To date, the survey has been filled out for 34 use cases, resulting in detailed information on features for these use cases. For each use case in the survey, we refer to its respective UCF from 3 – Use Cases. Consequently, the survey yields the first metrics for feature-related

KPIs. It shows that the UCFs differ in their feature requirements. This could provide valuable insights regarding the standardization roadmap by highlighting which specific features should be prioritized and the timeline for their implementation.

Fig. 20 shows the process how the use case collection in combination with survey results and support from the harmonization task force enabled a mapping of features and UCFs.

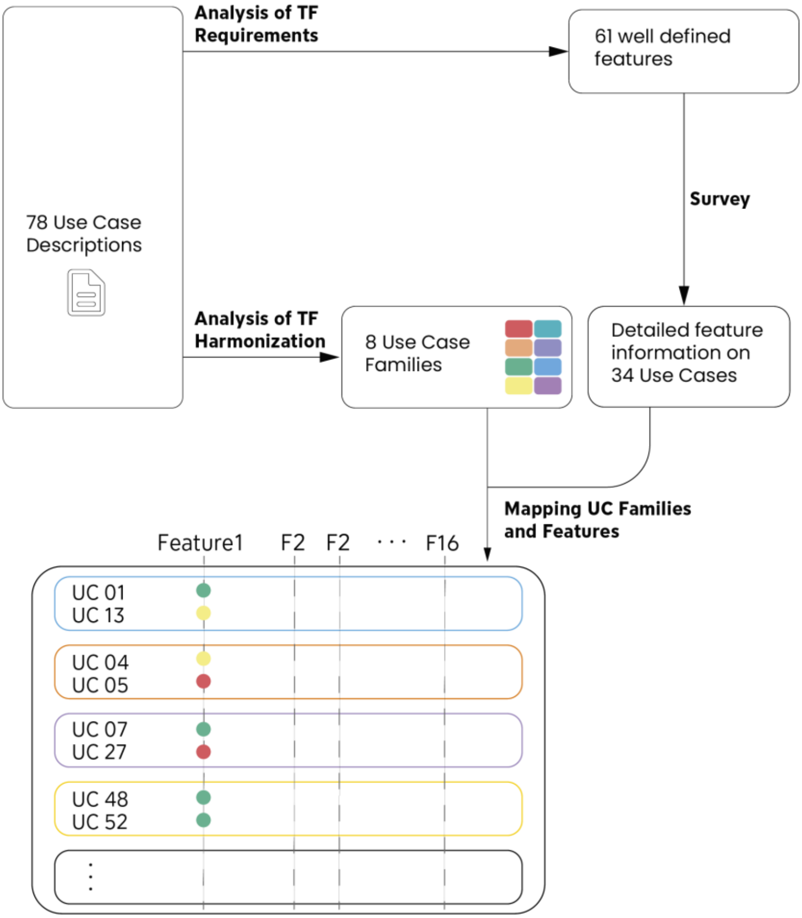

Fig. 20: Process from use case collection to the mapping of UCFs and features in this chapter.

Fig. 21 shows the distribution of UCFs for the use cases that contributed to the survey on features. 3D Mobility and Collaborative Robots have the most contributions, with 20% of the use case contributions, followed by Resilient

Society with 17.1%, and Fully Connected World with 14.3%. The survey yielded fewer use cases for Environmental Awareness (8.6%), Immersive Experience (8.6%), Digital Twins (5.7%), and Trustworthy Environments (5.7%). Subsequently, the upcoming analysis on UCF level may be a bit more meaningful for the UCFs 3D Mobility or Collaborative Robots compared to Digital Twins or Trustworthy Environments. Two survey contributions were not attributed to any UCF since they did not meet the definition of a use case as in 3 – Use Cases (not shown).

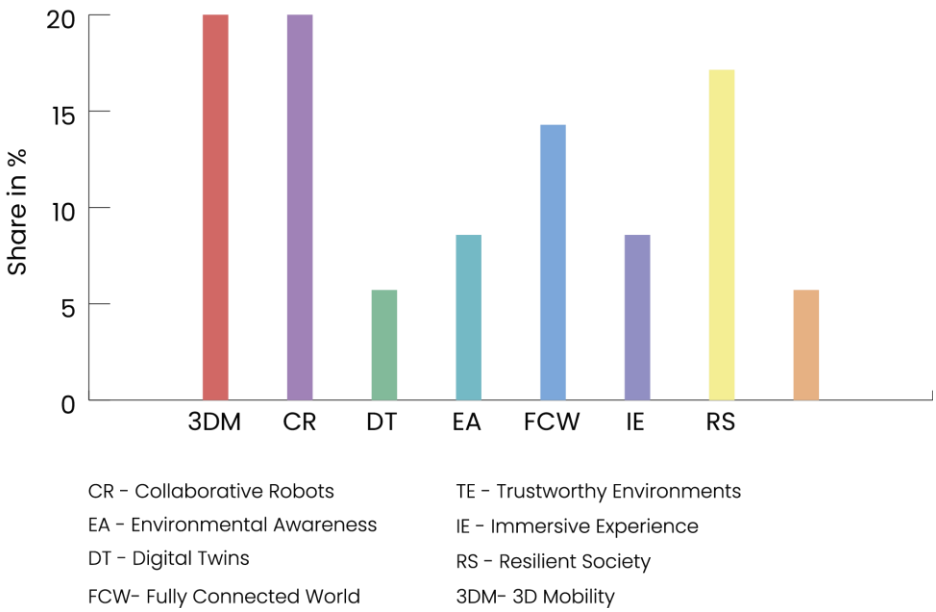

Fig. 21: Distribution of UCFs in the survey results.

To get more insights on features that are particularly significant for the realization of new use cases with 6G, we provide more details on features that were demanded by at least 25% of the use cases contributed to the survey and benefit at least one UCF. The features that do not fulfill this requirement are shown in Appendix A.2 - Feature Definitions in the Survey on Requirements. We define a UCF significantly benefiting from a specific feature if at least 66% or three of the family's UCs require the feature. In the following sections, we group the features into four categories: architecture, network capabilities, trustworthiness, and regulation. These categories shall provide a dedicated view of how the network design and capabilities are expected to change with 6G.

Each category also offers some subcategories that we call "feature categories", since they group similar features. The actual analysis is provided on a feature level; we analyzed each feature's potential as an enabler for the UCFs.

Fig. 22 shows the hierarchy of categories, subcategories and features with the example of the subcategory Network Monitoring: It is above the features **Network status information** and **Predictability of the Network KPI**, while it is below the category "Architecture".

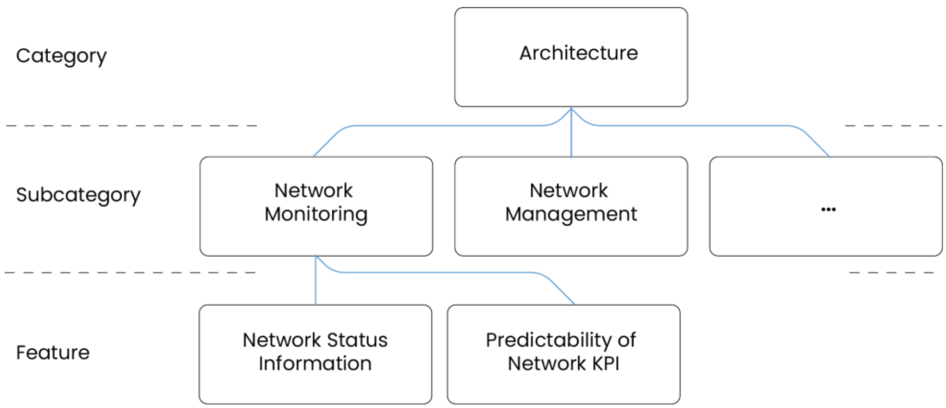

Fig. 22: Example of the analysis structure including category, subcategory, and features.

5.1 – Architecture

The contributed use cases raised many requirements with architecture-related implications. A significant share of use cases demanded network monitoring features, mainly network status information and predictability of network KPIs. While network status information reflects current conditions with a KPI on the tolerable delay for status updates, predictability of the network KPI provides information on future conditions for a specific forecast horizon. Also, the capability of nodes in a 6G network to have multiple connections to other nodes implies potential additional requirements for network management. In addition, traffic steering can handle traffic most efficiently and prioritize services according to their demands. Ensuring efficient operation can also require the network to allow changes and to self-organize itself to react and adapt to changes, e.g., when new nodes are created. Another central feature is self-healing, which describes the ability of the network to automatically turn off a broken link and reroute the data along a different path. Another novel, relevant feature concerning the network topology is the network of networks, which means a system is composed of multiple individual networks. These operate independently but are interconnected with the others for communication and collaboration purposes. Finally, a relevant feature in the scope of 6G is 3D networks, which refers to an integrated communication architecture among three dimensions: ground, air, and space. The first part of the architecture features is shown in Table 9, and their significance for the UCFs highlighted in yellow.

Table 9: UC Families and Architecture Features.

Feature	*Resilient Society*	*Digital Twin*	*Fully Connected World*	*Collaborative Robots*	*3D Mobility*	*Immersive Experience*	*Environmental Awareness*	*Trustworthy Environments*
Network status information								
Predictability of network KPI								
Multi-connectivity IoT nodes								
Traffic steering / traffic control								
Allow network changes								
Self-healing network								
Network of networks								
Holistic 3D network								

5.1.1 – Network Monitoring

Two particularly important features are in the network monitoring requirements category. **Network status information** especially benefits the UCF *Collaborative Robots*. To realize this UCF, network status information should be available after about 10 ms delay. For all UCFs, the demanded waiting times range from 8 to 3000 ms.

Another cornerstone for developing 6G is the feature **Predictability of Network KPI**. The survey results clearly indicate its benefits for the UCF *Fully Connected World*, and it is also a popular request among many use cases from *Collaborative Robots* and some from *3D Mobility*. The required forecast horizons range from 1 to 10 seconds with demanded KPIs for reliability, availability, and timing behavior. Further predictability requests included predicting the choice of the RAN technology if there is more than one alternative or also which link to use for a planned transmission. A *Resilient Society* use case asked for trajectories and handovers to be predicted. Sensing-related tasks with high-reliability requirements also call for dedicated radio nodes that need predictability.

5.1.2 – Network Management

The features in the network management feature category were targeted with yes/no questions rather than requests for statements on specific KPIs or metrics. **IoT Nodes with multi-connectivity** are an important cornerstone for the development of 6G since they enable the UCF *Collaborative Robots* and, to a slightly lesser extent, *3D Mobility*. Potential applications for multi-connectivity IoT nodes include communications among AGVs and their control centers in drone use cases and for use cases implemented on the shopfloor.

A central feature of 6G is **Traffic steering / Traffic control**. It clearly benefits six UCFs – *3D Mobility*, *Fully Connected World*, *Collaborative Robots*, *Resilient Society, Digital Twins,* and *Immersive Experience*. This may be relevant because AGVs can have different rights of way. Further applications include the gateway between the underlayer and overlayer networks. Regarding immersive experience applications, it could enable organizing streams based on client and subnetwork locations and reassign clients to video servers based on subnetwork capacities.

In addition, 6G should offer the possibility of a **network allowing changes in its settings**, meaning the network self-organizes and adapts to changing network or framework conditions. For example, this could mean that a new node created by a high-altitude platform is automatically integrated into the network and adequately considered for the best routing of any traffic: This feature would benefit *3D Mobility*, *Collaborative Robots*, *Digital Twins*, *Fully Connected World*, *Environmental Awareness*, and *Resilient Society*. Examples provided by actual use cases include changing the right of way for AGVs from the control center. Similarly, there may be applications where UAVs need to change their operation modes dynamically. Also, client-to-server associations may need to be reorganized following changes in the network. In addition, the ability of a network to self-organize poses novel challenges: In the case of an NTN, operation parameters need to be recorded to maintain a coherent signal processing, or, more generally, the potential consequences on load and other use cases must be known before applying changes.

Lastly, **self-healing capabilities** emerge as a crucial 6G feature. Its benefits extend to the UCFs *Resilient Society*, *Trustworthy Environments, Environmental Awareness, Immersive Experience*, *Collaborative Robots*, and *3D Mobility*. Many use cases have requested the application server, network, and devices to be self-healing, with a significant number targeting all components to be self-healing. More specifically, healing could mean finding alternative routing if a RAN or transport link gets lost. For simpler use cases, a sensing task performed by a BS could be taken over by a neighboring BS. In shopfloor applications requiring high reliability and QoS, healing functionality could be implemented via optimization executed by a network's digital twin or as a joint solution between a network and a production digital twin. It could also be implemented by reassigning clients and servers if the outage is predictable.

5.1.3 – Network Topology

From the feature category of network topology, a **network of networks** stands out since many use cases from the families *Fully Connected World* and *Resilient Society* require it. It also benefits some *Collaborative Robots, Environmental Awareness,* and *3D Mobility* use cases. For use cases including sensing, data fusion from multiple networks, i.e., sensors, could enhance the sensing capabilities. Also, the collaborative tasks could benefit if organized in a network of networks.

The **holistic 3D network** is a key feature in the realization of 6G, as it brings significant benefits to the UCFs *Resilient Society* and *Collaborative Robots*. While not frequently requested there, it could also extend capabilities and improve data quality in *Environmental Awareness* use cases. Furthermore, NTNs in the 3D network might enhance sensing capabilities or coverage.

5.1.4 – Device

The subcategory “device” refers to end devices and nodes or entities in the middle of the network. Important features are high levels of autonomy, cost-effectiveness, advanced mobility, and self-localization. While cost-effectiveness is a topic that has always been important, it deserves even more attention in the context of 6G, due to increased attention to societal values such as sustainability. Mobility and mobile network nodes are changing significantly towards 6G. Since 6G shall connect vehicles, AGVs, subnetworks, and other agents, many of which are moving with potentially high velocities. Additionally, many of these need the ability to self-localize.

Table 10: UC Families and Architecture Features (cont'd). If there is no specific legend for a feature, yellow ■ indicates a metric-independent high relevance and enabling potential of the feature.

Feature	**Legend**	*Resilient Society*	*Digital Twin*	*Fully Connected World*	*Collaborative Robots*	*3D Mobility*	*Immersive Experience*	*Environmental Awareness*	*Trustworthy Environments*
High autonomy level		yellow		yellow	yellow	yellow	yellow	yellow	yellow
Cost-effectiveness		yellow		yellow	yellow	yellow			yellow
Multi-RAT		yellow		yellow	yellow	yellow			
Mobility / mobile network nodes *KPI: supported velocity*	green ■ < 10 m/s yellow ■ 10...120 m/s red ■ >120 m/s	yellow		yellow	green	red	red	red	
Self-localization		yellow			yellow	yellow		yellow	
Active network selection *KPI: network change completion time*	red ■ <=1 s yellow ■ >1 s	yellow		red					
Cloud computing						yellow	yellow	yellow	yellow
Edge cloud computing					yellow	yellow	yellow	yellow	
Edge cloud computing for AI/ML					yellow	yellow		yellow	

Table 10 shows how the remaining architecture features, starting with device features, relate to the different UCFs. The essential 6G features in the device's feature category are cost-effectiveness, mobility, and self-localization. Surprisingly, **cost-effectiveness** was not explicitly requested by all use cases or a significant portion of UCFs. A reason for that may be that some use case authors raised concerns that low-cost components might not fulfill the technical requirements or that cost-effectiveness, while decisive for later adoption of the use cases, is not at the core of the use cases themselves. Still, cost-effectiveness is critical and frequently mentioned in use cases from *3D Mobility*, *Resilient Society*, *Fully Connected World*, *Collaborative Robots*, and *Trustworthy Environments*.

A **high autonomy level** is a significant cornerstone for the development of 6G since it particularly benefits the use case families of *3D Mobility*, *Collaborative Robots*, *Fully Connected World*, *Resilient Society*, *Environmental Awareness, Immersive Experience,* and *Trustworthy Environments*. While it may not be the primary concern in shopfloor applications that typically operate infrastructure-based, it can still be applicable if that is not the case. It could be desirable for interactions between robots and cobots, i.e., in environmental sensing use cases.

Multi-Radio Access Technology (multi-RAT) is an important feature since the UCFs *3D Mobility*, *Collaborative Robots*, *Fully Connected World*, and *Resilient Society* would particularly benefit from it. Selected *Environmental Awareness* use cases could also benefit from it since combining, e.g., JCAS data from different network operators might increase sensing accuracy and QoS. Another application mentioned in the survey is for a subnetwork controller to handle external links to 3GPP or NTN solutions.

Mobility / mobile network nodes would benefit the use case family *Fully connected world*. However, the feature also plays a significant role in *Collaborative Robots*, *3D Mobility*, and *Resilient Society*. The velocities of the mobile network nodes vary considerably from 2 to 200 m/s and vary among the different UCFs. The most demanding UCFs are *Environmental awareness*, *3D Mobility*, and *Immersive Experience*, which include nodes with more than 120 m/s. *Collaborative Robots*, on the other hand, move with only up to 7 m/s. The reasons for this variety in the provided numbers are in the kinds of nodes relevant in the different UCFs: While in *Environmental Awareness* and *3D Mobility*, UAVs or planes are often considered, the *Collaborative Robots* use cases happen at the shopfloor/factory floor with significantly slower AGVs. Even if drones are involved, their velocities would not exceed 30 m/s. Further frequently mentioned nodes with medium velocities are cars and trains.

Self-localization especially benefits the use case family *Collaborative Robots*. The feature would also support the UCFs *3D Mobility, Environmental Awareness,* and *Resilient society*. In particular, self-localization could be exploited so that Doppler shifts could be pre-compensated for satellite communications. Also, in aerodrome vicinities, current GPS precision could be improved with self-localization support. Another application is for asset tracking use cases, where the network optimization of a network digital twin could benefit from interaction with a production digital twin.

5.1.5 – Flexibility

While many use cases do not generally demand **active network selection**, it seems particularly important for the use case family *Fully Connected World and,* to a lesser extent, *Resilient Society*. In order to fulfill the demands of this use case family, a network change should happen in 1 second. Other UCFs such as *Environmental Awareness* would be less demanding with a limit of 10 to 100 seconds. Active network selection can become applicable following various causes: Most use cases refer to availability or coverage issues; however, capacity, timing behavior, or regulation-based criteria are also proposed. In immersive experience use cases with high streaming demands, it could help to optimize the data flow for better service quality. Also, the sensing network could be selected in 3D mobility use cases. Similarly, in sensing or observation networks with receivers that do not necessarily or not always contribute data to a land observation system, for example, the option to connect to a network contributing to the observation system would be an enabler.

5.1.6 – Computing

To meet the computing demands associated with 6G, cloud computing and edge cloud computing are features required by many use cases. The use case family *Environmental Awareness*, in particular, has high requirements here. Besides, *3D Mobility, Immersive Experience*, and *Trusted Environments* are UCFs clearly benefiting from **cloud computing**. In addition, *3D Mobility*, *Collaborative Robots*, *Environmental Awareness*, and *Immersive Experience* would highly benefit from **edge cloud computing**. A concrete application is the optimization and allocation of computation resources in the context of subnetworks, especially to convey information on changes in subnetwork topologies to an application layer. Ultimately, **AI/ML computing** is an important cornerstone for developing 6G. It would mainly benefit the UCFs *3D Mobility, Immersive Experience, Environmental Awareness,* and *Collaborative Robots*. The AI/ML applications provided in the use cases target the applications enabled by the network, which is object detection, object localization, or deriving aggregated metrics from multiple localized objects.

5.2 – Network Capabilities

6G will also pose novel requirements for network capabilities. One subject of interest regarding the network capabilities is the backhaul, which some use cases require. Many new applications will demand novel localization or sensing capabilities. This includes 3D sensing with accuracy, resolution, and separability requirements and providing those capabilities over a specific service area. Table 11 shows how these features would benefit the different UCFs. For localization accuracy, resolution, separability, and service area, there are KPIs with specific metrics that enable color-code ordering according to the cruciality of the feature.

Table 11: Network capabilities and UC Families. If there is no specific legend for a feature, yellow (yellow) indicates a metric-independent high relevance and enabling potential of the feature.

Feature	**Legend**	*Resilient Society*	*Digital Twin*	*Fully Connected World*	*Collaborative Robots*	*3D Mobility*	*Immersive Experience*	*Environmental Awareness*	*Trustworthy Environments*
Scalability		yellow			yellow	yellow	yellow	yellow	
Device density	(green) <0.01 m^{-2} (yellow) 0.01…1 m^{-2} (red) >1 m^{-2}		red		yellow	red			
Capacity / Backhaul		yellow		yellow		yellow			
Near-zero energy consumption in idle						yellow			
Transmission Time	(red) <1 ms (yellow) 1…100 ms (green) >100 ms	green		red	yellow	red	yellow		green
Update Time	(red) <1 ms (yellow) 1…100 ms (green) >100 ms	green		red	yellow	yellow	yellow		green
Response Time	(red) <1 ms (yellow) 1…100 ms (green) >100 ms			red	yellow	yellow	yellow		green
Synchronization *KPI: deviation*	(red) <=0.1 ms (yellow) >0.1 ms			red	yellow	yellow			

3D Sensing									
Location accuracy	<10 cm 10 cm…1m >1 m								
Resolution and Separability	<10 cm 10 cm…1m >1 m								
Service Area *KPI: range*	<= 1 km > 1 km								
Sensing estimate update rate	< 5 Hz 5…100 Hz > 100 Hz								

5.2.1 – Coverage

Scalability is an important coverage-related pillar for the development of 6G. It would benefit the UCFs *3D Mobility*, *Collaborative Robots, Immersive Experience, Environmental Awareness*, and *Resilient Society*. In particular, in use cases where the network configuration is adjusted following the application's demand, the possibility of scaling up the network with a growing demand would be a big improvement.

Furthermore, **device density** is a significant 6G aspect, which would primarily benefit the UCFs *3D Mobility*, and *Collaborative Robots*. The demanded device densities range from 0.001 to 1-10 devices per square meter. High demands could, for example, result from applications in stadiums or smart factories.

5.2.2 – Capacity

An important capacity-related cornerstone for the development of 6G is the increased **backhaul** requirements. In particular, an advanced backhaul would benefit the use case family *Resilient Society*. More specifically, *Resilient Society* use cases with backhaul requirements demand fiber-based high-speed core access, backhaul redundancy, and operation with and without backhaul. Further UCFs profiting from an advanced backhaul are *3D Mobility* and *Fully Connected World*. Drivers for advanced backhaul requirements are high data rates of 10 Gbit/s, nomadic networks, or the backhaul serving as a gateway to cloud services.

5.2.3 – Sustainability

From the sustainability subcategory, the only feature significantly benefiting a use case family is **near-zero energy consumption in idle mode**, which is an enabler for the use case family of *3D Mobility*. However, there is also an example of how it could ease production-related digital twins use cases if the energy demand of devices in a smart factory could fully be met by energy harvesting methods.

5.2.4 – Timing Behavior

Transmission time [4] benefits *3D Mobility*, *Collaborative Robots*, *Fully Connected World, Immersive Experience*, and *Resilient Society*. Allowed mean transmission times range from “instantly” for a *Resilient Society* use case to 10 ms. The more often requested strict upper bound starts at <1-2 ms for a *Fully Connected World* use case, while most use cases demand strict upper bounds between 5 and 50 ms. One very demanding use case in *3D Mobility* requires transmission times below to 0.1 ms. At this early stage of the use case formulations, the exact numbers often remained unclear because of other dominating challenges to be solved first or unclear constraints, e.g., the transmission time may depend on the type of AGVs participating in a use case. Also, some use cases apply to different scenarios with different transmission time requirements.

Update time benefits *3D Mobility*. A 10 ms update time is most often required; however, a *Fully Connected World* use case stands out with a maximum permissible update time of 0.25 to 4 ms with a deviation of considerably less than 1 ms. Update time has similar uncertainties as transmission time. However, specific update times could be formulated for periodic traffic with known cycle times or for digital twin use cases in smart factories where the network digital twins need to communicate with the application promptly.

Similar findings apply to **response time**. It benefits the UCFs *Collaborative Robots* and *Fully Connected World*. The required strict upper bounds for response time are < 1-4 ms for a *Fully Connected World* use case and 5-9 ms for the *Collaborative Robots* use cases. The qualitative concerns raised by the use case authors closely align with update time and transmission time.

Finally, **synchronization** benefits some use cases, in particular, from the *3D Mobility*, *Collaborative Robots*, and *Fully Connected World* UCFs. The allowed maximum deviations are primarily around 1 ms, but they go down to 0.1 or even 0.002 ms. The feature is particularly important for multi-static sensing applications where Tx-Unit and Rx-Unit (the sniffer) must be synchronized. Some applications may depend on the protocol. Furthermore, the synchronization requirement may also depend on the transmitted data type – a critical case would be audio samples from different sources.

5.2.5 – Localization & Sensing

Localization and sensing features were demanded by many use cases. One of the important building blocks for 6G might be **3D sensing**. This feature would especially benefit the use case family *Environmental Awareness*. Furthermore, it would benefit *3D Mobility* and *Collaborative Robots*.

Localization accuracy requirements, describing how close a measurement is to its true value, were particularly requested by and would benefit the UCFs *Collaborative Robots* and *3D Mobility*. While to realize *3D Mobility* use cases, only an accuracy of 50 cm would need to be achieved, *Collaborative Robots* use cases demanded accuracies around 1 cm. The high accuracies required by collaborative robot use cases employ AMRs, for example, to accurately position industrial goods. It can also be a safety-critical requirement in UAV and AGV use cases since accuracy is needed to avoid collisions.

Another important feature of 6G is **sensing resolution and separability for localization.** While this is related to the sensing accuracy, it is a slightly different concept: The resolution is the minimum difference between two targets to have measurably different results. This would particularly benefit the UCFs *Environmental Awareness* and *3D Mobility*. For the *3D Mobility* use cases, a resolution and separability of 50 cm would be sufficient; the *Environmental Awareness* use cases raised more relaxed requirements of 1 to 10 meters.

Service area/sensor coverage is a significant cornerstone for developing 6G due to its critical role in the UCFs *Environmental Awareness* and *Resilient Society*. While other UCFs' ranges reach up to 15 meters, the demands for *Environmental Awareness* range from 10 to 20 km.

While **sensing estimate update rate** was only requested by very few use cases, the provided numbers indicate more demanding requirements of up to 100-5000 Hz for the UCFs *Immersive Experience* and *Environmental Awareness* compared to *3D Mobility* and *Resilient Society* with up to 5 Hz.

5.3 – Trustworthiness

Trustworthiness, in the context of 6G, must be implemented in the system's design and guaranteed during its service on each layer. In the context of networks, trustworthiness refers to meeting the stakeholders' expectations through security, privacy, reliability, resilience, availability, and safety [16]. In our use case analysis, fidelity and message loss were additional relevant topics, while safety was underrepresented. From the privacy domain, NPNs evolved as a crucial feature. Table 12 shows how certain trustworthiness features benefit the different UCFs.

Social acceptance is another important feature of 6G development. It is the result of a process where stakeholders and project leaders work together to find solutions to acceptance barriers and objections. Social acceptance could significantly benefit the UCFs *3D Mobility*, *Fully Connected World*, and *Resilient Society*.

Furthermore, **fidelity** seems a critical cornerstone for the development of 6G. Fidelity is the quality of being faithful in that a transmitted signal represents the original information. It is specially requested by *Digital Twins*, *Trustworthy Environments*, *3D Mobility*, *Resilient Society*, and *Fully Connected World* use cases with demanded percentages ranging from 70% to 100%. The *Resilient Society* use cases targeted the most challenging values of 99% to 100%. *Trustworthy Environments* requested fidelity percentages of up to 99%.

Also, the feature **security-by-design** should play a significant role in the development of 6G. In particular, it would significantly benefit the UCFs *Resilient Society*, *Collaborative Robots*, *Trustworthy Environments*, *Immersive Experience*, *Fully Connected World*, and *3D Mobility*.

Another strong emphasis should be placed on **availability**. It is the ability of a network to perform the required functions or processes at any given time. The corresponding metric refers to the probability of the system functioning at that time. Progress in availability would, in particular, benefit the use cases from *Fully connected world*, *Collaborative Robots*, *3D Mobility*, *Trustworthy Environments*, and *Resilient Society*. To enable the use cases from *Fully connected world* and *Collaborative robots*, availabilities of 99.9999% were requested. The requirements for *3D Mobility*, *Trustworthy Environments*, and *Resilient Society* have slightly lower but still challenging demands for availability of 99.999%.

Table 12: Trustworthiness and UC families. If there is no specific legend for a feature, yellow indicates a metric-independent high relevance and enabling potential of the feature.

Feature	**Legend**	*Resilient Society*	*Digital Twin*	*Fully Connected World*	*Collaborative Robots*	*3D Mobility*	*Immersive Experience*	*Environmental Awareness*	*Trustworthy Environments*
Social acceptance		yellow		yellow		yellow			
Fidelity	red: >98 % yellow: 80...98 % green: <80 %	red	yellow	yellow		yellow	green		red
Security-by-design		yellow		yellow	yellow	yellow	yellow		yellow
Availability	red: >99.999 % yellow: 99... 99.999% green: <99 %	yellow		red	red	yellow	green		yellow
Message loss	red: <0.001 % yellow: 0.001... 0.1 % green: >0.1 %	yellow			red	yellow	green		
Resilience		yellow			yellow	yellow	yellow		yellow
NPNs		yellow			yellow	yellow	yellow		yellow
Zero-trust		yellow			yellow	yellow			yellow

A further topic of trustworthiness for the development of 6G is **message loss**. It occurs when one or more packets transmitted across a network drop before reaching their destination, producing an error in the transmitted data. This is particularly relevant for the UCFs *Collaborative Robots*, *Resilient Society*, *Immersive Experience*, and *3D Mobility*. Especially *Collaborative Robots* use cases raise critical message loss requirements with message loss probabilities below 0.0001%.

Resilience is a trustworthiness feature that allows a network to provide and maintain an acceptable level of service despite various faults and challenges to normal operation. It is an essential 6G cornerstone due to its benefits for the UCFs *Collaborative Robots*, *Trustworthy Environments*, *Immersive Experience*, *Resilient Society*, and *3D Mobility*.

Regarding privacy, **NPNs** seem significant for the development of 6G and can be standalone networks or integrated into a public network and rely or not rely on network functions from an MNO. They are highly beneficial for realizing use cases for a *Resilient Society*, *Trustworthy Environments*, *Environmental Awareness*, *3D Mobility*, and *Collaborative Robots*.

Zero-trust is a security model that requires strict identity verification for every person and device trying to access resources on a non-public network, regardless of whether they are sitting within or outside the network perimeter. Zero-trust is essential to developing 6G since it clearly benefits the UCFs *3D Mobility*, *Resilient Society*, *Collaborative Robots*, and *Trustworthy Environments*.

5.4 – Regulation

Highly demanded features from regulation were licensing, interoperability, and flexible regulation, as shown in Table 13. **Licensing** is an important aspect since it particularly benefits the following UCFs: *Immersive Experience*, *Trusted Environments*, *Collaborative Robots*, and *Resilient Society*. The UCFs *Fully Connected World* and *Trusted Environments* would highly benefit from the feature **interoperability** and **flexible regulation** based on the survey feedback. In addition, flexible regulation is an enabler for the *Environmental awareness* use case family. Licensing in the context of 6G mainly refers to permissions to use specific portions of the radio spectrum. In contrast, flexible regulation emphasizes the flexible management of frequencies based on flexible, non-discriminatory, and pro-competitive criteria to ensure efficient and interference-free use of network services. Interoperability is the ability to communicate with peer systems, relating them together and removing incompatibilities between them.

Table 13: Regulation and UC Families. Yellow ■ indicates a metric-independent high relevance and enabling potential of the feature.

Feature	*Resilient Society*	*Digital Twin*	*Fully Connected World*	*Collaborative Robots*	*3D Mobility*	*Immersive Experience*	*Environmental Awareness*	*Trustworthy Environments*
Licensing	■			■		■		■
Interoperability	■		■	■				■
Flexible regulation			■				■	■

6 – Discussion

In this chapter, we summarize the essential takeaways from the analysis of presented 6G use cases, technology building blocks, and features and requirements. Additionally, we highlight the main differences and agreements with the Hexa-X and Hexa-X-II initiatives that we have also aligned our findings.

6.1 – Use Cases

In this white paper, we provide a snapshot of several 6G UCs, contributed by researchers and industry experts in Germany. Five of the UCFs in our white paper, namely *Collaborative Robots, Digital Twins, Immersive Experience, Fully Connected World, and Trustworthy Environments*, are closely aligned with use case areas already defined in the prominent European 6G project, Hexa-X-II. By aligning our new use cases within these established categories, we aim to reinforce a cohesive and integrated vision for 6G that complements ongoing European 6G standardization efforts. This also allows us to contribute fresh perspectives while remaining consistent with a broader 6G framework.

6.1.1 – Summary and Interpretation of the UCFs

In addition to the aforementioned UCFs, we introduce three novel UCFs, *Resilient Society, 3D Mobility, and Environmental Awareness*, reflecting unique aspects of 6G Platform's vision for 6G. There are several takeaways and highlights that we can conclude from these novel UCFs.

Resilience is a foundational concept throughout the UCs, encapsulating the reliability, robustness, and safety in 6G ecosystems and their capacity to address safety and security across various domains. Beyond resilient connectivity, as specified in *Resilient Society*, several new UCs aim to build a comprehensive technological ecosystem that safeguards individuals, infrastructure, and environments against disruptions and adversaries.

Environmental Awareness extends beyond creating energy-efficient networks; it aims to adapt human activities and industries to environmental needs and changes. As an essential enabler of sustainability, 6G technologies can support real-time environmental monitoring, data-driven resource management, and energy efficiency. This perspective reflects a broader objective: not only to reduce the ecological footprint of cellular networks but also to leverage communication technologies to respond to environmental changes that impact society at large.

3D Mobility emphasizes the importance of advanced networking technologies, especially as cities integrate vertical mobility solutions like UAVs. This push highlights the harmonization needed between different types of mobile entities, from ground vehicles to airborne drones, necessitating connections with high-reliability and predictable timing behavior that can support safe and efficient mobility in all dimensions.

All UCFs share many complementary and interdependent elements, underscoring the interconnected nature of 6G use cases. For instance, *Resilient Society* and *Trustworthy Environments* emphasize societal safety and security and would benefit from each other's advancements. The *Fully Connected World* could be seen as an overarching framework highlighting 6G-enabled extended connectivity that fosters many UCs under *Environmental Awareness* and *3D Mobility*. Additionally, *Digital Twins* in the context of 6G can enable advanced applications for *Collaborative Robotics*, allowing for sophisticated monitoring and optimization in various work settings. Such cross-category synergies show that these use cases are less isolated than they initially appear, highlighting how the unified capabilities of 6G can enhance diverse applications.

The use cases outlined in each UCF span multiple sectors and applications, ranging from industrial automation and manufacturing to urban planning, transportation, agriculture, and beyond. Each of these sectors involves diverse stakeholders, including regulators, manufacturers, service providers, and end-users, making collaboration essential to realize the full potential of 6G. As the technology develops, these multi-stakeholder engagements will play a vital role in shaping a robust, secure, and sustainable 6G ecosystem.

6.1.2 – Comparison to Hexa-X-II

Our analysis often shares a similar perspective with Hexa-X-II on the importance of core 6G themes. We adopt some of the existing UCFs, namely *Collaborative Robots, Digital Twins, Immersive Experience, Fully Connected World,* and *Trustworthy Environments*, to harmonize with established European 6G efforts. Nevertheless, we distinguish from the Hexa-X findings both methodologically and in content focus, leading to unique insights into 6G's role and setting new directions for exploring 6G applications.

Methodologically, we focus primarily on high-level application scenarios, providing an easy-to-read and coherent overview of 6G's potential impact. By decoupling these scenarios from detailed technical requirements and implementation specifics, we enable a streamlined presentation of use cases. At the same time, we provide insight into each scenario's connection to emerging 6G features, allowing readers to grasp both the applications and their alignment with the broader 6G ecosystem.

Content-wise, we extend the Hexa-X-II's 6G vision through three new UCFs: *Environmental Awareness, Resilient Society*, and *3D Mobility*. *Environmental Awareness* emphasizes 6G's role in advancing environmental visibility for climate monitoring, pollution control, and sustainability, distinguishing it as one of the central themes rather than a result of increased connectivity as presented in Hexa-X-II. *Resilient Society* highlights 6G's potential for building defensive measures and prioritizing protection against adversarial threats more prominently than the disaster resilience emphasized in Hexa-X-II. Finally, *3D Mobility* puts forward new connectivity and coordination challenges for emerging aerial and urban mobility, positioning 6G as crucial to the seamless integration of various mobile platforms in future smart cities. From this broadened perspective with new UCFs, we bring a new perspective on the analysis of several use cases shared with Hexa-X-II as well.

Through these methodological and thematic distinctions, our analysis offers a fresh perspective on 6G use cases, presenting unique conclusions about how 6G technologies can shape the future.

6.2 – Technical Building Blocks

In addition, we developed key technical building blocks (TBBs) necessary for enabling the collected use cases and use case families, respectively. Overall, we have found seven key TBB categories and 29 TBBs essential for the successful development of 6G technologies. These extend the vision of 6G, providing a future-ready ecosystem to address complex societal and industrial needs.

6.2.1 – Summary and Interpretation of the TBBs

The contribution on TBBs is in the definition of the aforementioned seven main categories of TBBs and a total of 29 TBBs related to the development of 6G technologies. The categorization of the TBBs was conducted in accordance with the specifications of the Hexa-X-II project. The TBBs identified in the use cases were organized in a systematic manner and classified according to Hexa-X-II's five primary enablers [11]: "AI Enablers for Data-Driven Architecture," "Network Modularization," "Architectural Enablers for New Access and Flexible Topologies," "Network Beyond Communication," and "Virtualization and Cloud Continuum Transformation." Two additional TBB main categories were introduced. Subsequently, the TBB were assigned to various subcategories, resulting in the development of the described structure:

1. Integrative AI Solutions for Network and Application Enhancement: This category focuses on utilizing AI across various network layers to inter alia optimize infrastructure, management, and service capabilities.

2. Comprehensive Network Systems and Services: It emphasizes a modular architecture aimed at enhancing adaptability and scalability through software-defined networking.

3. Advanced Network Architectures and Connectivity Solutions: This focuses on flexible networking solutions, allowing seamless interoperation between different network types like TNs and NTNs.

4. Converged Network Systems and Advanced Communication Technologies: This category explores the integration of communication and sensing technologies, highlighting new capabilities from higher frequencies and quantum technologies.

5. Integrated Cloud-Edge Ecosystem Transformation: It covers the transformation involving edge and cloud computing to enhance data processing and user experience while minimizing latency.

6. Air Interface: This category deals with technologies related to the physical layer and advanced antenna systems necessary for high performance in the 6G environment.

7. Orchestration and Management: This focuses on automating service configurations and resource management to meet user demands effectively.

The use cases authors were asked regarding the need of the individual use case for the defined TBB based on the three options “mandatory,” “optional,” and “not needed”. The results were then analyzed on a use case family level. Besides, the TBBs were categorized with respect to their temporal criticality by investigating their relevance over three development phases of 6G: Phase 1 defined from 2025 to 2028, representing the most urgent technologies that need to be/will be applied from the first release of 6G. Phase 2 corresponds to technologies expected to be standardized between 2028 and 2030. Phase 3 follows from 2030 and includes technologies that will be seen as futuristic and maybe beneficial for later usage but not currently mandatory. The definition of the phases was chosen in accordance with the latest discussions in 3GPP and industry alignments with respect the expected upcoming 3GPP 6G releases (till Rel. 23).

The key results regarding the TBBs and their categories for 6G development are given in the following:

1. Integrative AI Solutions:

- UCFs *CR*, *IE, TE* and *DT* state integrative AI solutions as beneficial and/or as needed.
- The most critical TBB is "Digital Twin, Simulation and Data Fusion" which is seen in Phase 1 of the 6G timeline, meaning a critical solution which has a high demand of applying it in the first generation of 6G. The others are predicted to be relevant for Phase 2 or even Phase 3 (later than 2029).

2. Comprehensive Network Systems and Services:

- There is a clear demand for comprehensive network systems and services for UCFs *TE* and *DT;*
- In general, the TBB and the corresponding sub-TBBs are deemed mandatory or beneficial for every UCF despite the TBB of cell-free architecture.
- In consequence, all TBBs (expect the cell-free architecture one) are indicated to be relevant for Phase 1. Cell-free architecture is stated to happen in Phase 3.

3. Advanced Network Architectures and Connectivity Solutions:

- Advanced network architectures and connectivity solutions and the corresponding sub-TBBs are indicated as mandatory or beneficial for most UCF: especially the UCFs *TE* and *FCW* highlight their need, whereas UCF *EA* concludes to have no need.
- Every sub-TBB is marked to be relevant for Phase 1.

4. Converged Network Systems and Advanced Communication Technologies:

- Converged network systems and advanced communication technologies have a mandatory character for UCFs *EA*, *DT*, *TE* and *RS*. On the other hand, UCFs *FCW* and *IE* state for most TBBs no need.

- The sub-category Quantum Technologies for Network Infrastructure is at least in the current state of development indicated as no need for nearly all UCFs. In consequence, this TBB is foreseen to happen in Phase 3.

- Despite ISAC (Phase 2), sensing, positioning and time synchronization as well as interoperability and service excellence are seen to happen in Phase 1.

5. Integrated Cloud-Edge Ecosystem Transformation:

- Most UCFs view the integrated cloud-edge ecosystem transformation as optional and not as a mandatory step forward, except UCFs *RS*, *3DM* and *IE* which stated a medium mandatory need.

- Both edge computing innovation and computing architectures and technologies are classified to be relevant for Phase 2.

6. Air Interface:

- The TBB air interface is diverse, however most UCFs do not explicitly mention the air interface as a critical TBB. Nevertheless, there are e.g. sub-TBBs like multi-antenna beamforming and beam management which UCFs like *EA* and *CR* see as mandatory.

- Besides, advanced transceiver technologies are stated to be relevant for several UCFs and therefore referred to Phase 1.

- The UCFs stated no need for cell-free massive MIMO and in consequence, this TBB is related to Phase 3, same as the reconfigurable intelligent surface TBB. However, the RIS TBB is seen as beneficial by most UCFs, except for the UCF *FCW*, which states no need.

- With respect to spectrum, the frequency bands of FR1 and FR3 are indicated for a high need, corresponding to be relevant in Phase 1. FR2 is categorized to deployment in Phase 2 and frequencies in the THz band in Phase 3.

7. Orchestration and Management:

- The orchestration and management TBB as well as its sub-TBBs show a diverse but medium mandatory need across all UCFs.

- Especially, the security and trust TBB has to be highlighted as most UCFs state the mandatory character of this TBB. In consequence, it is situated within Phase 1.

6.2.2 – Comparison to Hexa-X-II

As stated above, the TBB categories were identified with respect to the Hexa-X-II's five primary enablers [11]: "AI Enablers for Data-Driven Architecture," "Network Modularization," "Architectural Enablers for New Access and Flexible Topologies," "Network Beyond Communication," and "Virtualization and Cloud Continuum Transformation.". These relate to the TBBs of the introduced TBBs “Integrative AI Solutions for Network and Application Enhancement,” “Comprehensive Network System and Services,” “Advanced Network Architectures and Connectivity Solutions,” “Converged Network Systems and Advanced Communication Technologies,” and “Integrated Cloud-Edge Ecosystem Transformation”, respectively. As the Hexa-X deliverable 3.2 aimed to initial describe the enablers and the reason and motivation why these enablers are important for the 6G architecture, a further gap analysis if these enablers and the sub-enablers (like “Enhancing Joint Communication and Sensing Capabilities” of the category "Network Beyond Communication") was done within the TBB taskforce. Besides, we analyzed deliverable 3.3 [17], summarizing Hexa-X-II's initial analysis of architectural enablers and framework and following up on deliverable 3.2.

The TBBs “Air interface” and “Orchestration and Management” and the corresponding sub-TBBs are additionally introduced in the presented white paper. The TBB “Air Interface” relates hereby strongly to enablers, defined by Hexa-X in deliverable 4.3 [18]. Especially, the antenna topics, like MIMO, RIS, but overarching the physical layer topics are represented. The Hexa-X-II deliverable 2.2 [12] on the other hand states on the enablers related to radio interface and protocols, next to ones related End-To-End (E2E) service management and automation perspective and enablers related to security, privacy and system level resilience, correlating with our TBB categories B, C and D.

The general architecture of the TBBs, shown in Fig. 12, relates and matches to a certain extent with the overall architecture and mapping of Hexa-X-II enablers to the architecture given in deliverable 3.3 [17] (compare Figure 2-

1, Figure 3-1, Figure 4-1, Figure 5-1, Figure 6-1 and Figure 7-1). Differences result due to the modification of the original enabler categories of Hexa-X-II by the TBB taskforce in accordance with the use case feedback. However, there are also consistencies like the data collection and AI framework as well as security aspects and orchestration and management crossing all layers for both the white paper and the Hexa-X-II approaches. On the other hand, TBBs with respect to the physical layer (TBB category “Air Interface”) are not included in the Hexa-X-II system architecture blueprint.

Further advanced aspects are to the best of the authors’ knowledge the TBB category “Orchestration and Management” with its subcategories G1 and G2. The aspect of the Cross-Layer/Cross-Operator interface for service control and management of data and information are crucial in fully connected worlds to ensure efficiency and reliability. Being interoperable with such kind of interface could be highly relevant, especially in environments where seamless integration is necessary. Besides, interfaces for exchanging SLA templates between network operators alongside the technology deliverable chain to enable automated transactions are foreseen to be highly mandatory and beneficial for UCF *FCW* and *IE*, respectively.

Furthermore, the direct link between the need of the TBB categories by the individual use cases and the overarching UCFs [3] is a major contribution of the presented white paper. The classification of the TBBs (or enablers) in three phases of 6G and in consequence, a roadmap of 6G are further achievements as these aspects are not provided in a comparable manner by the Hexa-X or Hexa-X-II projects.

6.3 – Features and Requirements

The German 6G projects’ vision for next-generation networks emphasizes adaptability, trustworthiness, network topology, and device management as foundational features. These align with expected industry trends and offer insights into specific needs for diverse and complex use cases, from autonomous mobility to immersive digital experiences.

6.3.1 – Summary and Interpretation of the Findings on Features

A key priority identified is the necessity for a resilient, multi-layered network architecture that supports use cases across different scales and conditions, from high-density urban areas to critical industrial environments. Features like self-healing capabilities and a network of networks topology reflect a sophisticated approach to maintaining continuity and reliability under dynamic or unpredictable conditions. For instance, self-healing functionality supports automated rerouting to address network disruptions, which is particularly crucial for the UCFs *Collaborative Robots* and *Resilient Society*, where uninterrupted service is essential.

Additionally, the holistic 3D network feature underscores the vision for 6G to provide a comprehensive framework for spatially aware applications. This is especially pertinent for *3D Mobility* and *Environmental Awareness*, suggesting that 6G network architecture will extend beyond surface-level connectivity to encompass multi-dimensional data flow, including NTNs and satellite integration. This approach could enhance data quality and coverage, facilitating environmental sensing and advanced robotics functionalities.

One of the defining characteristics of the 6G features is the emphasis on trustworthiness. This includes availability, security-by-design, message fidelity, and zero-trust models. The need for these security measures is notably high for the UCFs with an inherently high focus on trustworthiness, namely *Trustworthy Environments* and *Resilient Society*, which demand up to 99.9999% availability – a level that reflects the growing dependency on real-time, reliable networks for critical applications.

Requirements for mobility, edge computing, and localization align with expectations for high data rate communication with predictable timing behaviors across autonomous systems. The need for multi-connectivity in IoT nodes and robust edge computing infrastructure highlights a shift towards decentralized processing, essential for time-sensitive, data-intensive applications such as *Collaborative Robots*. Edge computing is expected to play a critical role in tasks such as traffic steering and real-time data analysis in *Environmental Awareness* and *3D Mobility* use cases, emphasizing the decentralized nature of future network architecture.

Unexpectedly, the survey indicated that cost-effectiveness was not a primary consideration across use cases, suggesting the project is focusing on technical feasibility and feature integration at this stage.

Also, the survey did not confirm sustainability or energy-efficiency related features as important cornerstones for the realization of 6G use cases. While near zero-energy consumption in idle mode can be beneficial for some shopfloor-related and *3D Mobility* use cases, it is not considered a major enabler for many use cases. The other energy efficient features, e.g., transceiver and multi-antenna systems' efficiency or energy per unit of traffic were not frequently demanded in any of the UCFs. However, for both cost and sustainability, this may change later as they become more pressing in the broader adoption of 6G.

Lastly, regulatory features such as flexible spectrum licensing and interoperability are essential for supporting cross-network functionalities and use cases from a *Fully Connected World*. Flexible regulations will allow 6G to adapt to the demands of specific regional requirements while promoting global interoperability. Although this adaptability is expected, the 6G vision confirms the necessity of regulatory frameworks that support rapid changes in technology and spectrum allocation without compromising performance or security.

6.3.2 – Comparison to Hexa-X-II

Hexa-X-II strongly emphasized positioning accuracy and AI/ML capabilities when evaluating how novel use cases pose challenges exceeding the capabilities provided by 6G [3]. Use cases related to *Immersive Experience*, *Future Mobility*, *Collaborative Robots*, and *Digital Twins* demand positioning accuracies better than 1 m and, in some cases, 10 cm. The 6G Platform's use case collection confirms these findings with many use cases from the families *3D Mobility* and *Collaborative Robots* demanding localization accuracies below 1 m. In fact, the requirements for position may be even higher with *Collaborative Robots* use cases calling for accuracies of 1 cm.

A similar picture results from comparing the mobility needs of both initiatives. Not only did the use case collections of both Hexa-X-II and 6G platform define the velocity of moving network nodes as an essential criterion to recognize future requirements in 6G, they also similarly identified the benefiting use cases of these mobility needs. The use case collections agree that *Collaborative Robots* do not have particularly high mobility demands. The representative use case in Hexa-X-II requires <20 km/h; our findings mainly yield similar velocities with applications targeting the factory floor. The only exception where higher velocities may be applicable in Collaborative Robots use cases is if drones are involved. However, our use case collection extends the mobility-related use case family (Hexa-X-II: Physical Awareness; 6G Platform: *3D Mobility*). While we agree in considering vehicles, trains, and drones, and corresponding velocities of up to 400 km/h, there are also use cases that include airplanes. These should be able to share their data with peers, too, for instance, in a subnetwork, with velocities of up to 900 km/h.

The initiatives also correspond that some 6G use cases will require transmission times below 1 ms. In the 6G platform's use case collection, this applies to the UCFs *Fully Connected World* and *3D Mobility*, while it is the *Collaborative Robots* use case family in Hexa-X-II with a transmission time of 0.8 ms. Nevertheless, there are use cases with single-digit ms transmission times in the 6G platform's use case collection, indicating that there are demanding timing needs in *Collaborative Robots* use cases.

Unexpectedly, 6G Platform use cases have lower requirements than the use cases of Hexa-X-II for the trustworthiness-related KPIs service availability and reliability. There are use cases in Hexa-X with five to eight 9s for availability and seven 9s for reliability, while four 9s for availability were requested in the 6G Platform's use cases.

In summary, the 6G Platform largely confines with the key trends on 6G enablers identified by Hexa-X-II on the feature (sub)category level, which are AI/ML computing, enhanced sensing and positioning capabilities, trustworthiness and NTN integration. On feature level, there are some different emphasizes since our findings rather stress availability as a key trustworthiness feature than privacy (Hexa-X-II) and don't see AI/ML as much as a characteristic requirement as Hexa-X-II does. However, this can also result from our framing being slightly more user-centric and less technical, rather targeting the benefit as a feature (e.g., resilience, privacy) than the technical requirement to realize it (e.g., AI with federated learning).

7 – Test and Measurement Challenges for 6G Technology Building Blocks

As the industry transitions towards the sixth generation (6G) of wireless communication, the landscape of test and measurement is set to encounter unprecedented challenges. The ambitious goals of 6G, including ultra-high data rates, extremely low latency, and seamless connectivity, demand rigorous testing and validation to ensure these expectations are met. This chapter explores the multifaceted testing and measurement challenges associated with 6G technologies, focusing on key areas such as AI, phased antenna arrays, ISAC, sub-THz frequencies, and XR-based applications. By understanding these challenges, we can develop robust testing methodologies that ensure the reliability, performance, and security of 6G systems, paving the way for the next generation of wireless communication.

7.1 – Challenges and Strategies for Validation of AI in 6G Systems

AI and ML reshapes the landscape of wireless communication networks, particularly in the context of 5G and beyond. While AI-driven solutions present significant opportunities, they also introduce unique challenges. This section examines critical aspects of data collection, validation, and testing for AI- and ML-based algorithms within wireless communication systems. From synthetic simulation of data to real-world field tests, offering strategies to ensure robustness, efficiency, and interoperability. Key focus areas include hyper-automation, model resilience, and energy efficiency.

7.1.1 – Data Collection: From Simulation to Field Data

Simulated scenarios provide controlled environments for testing AI- and ML-based algorithms, but the diversity and quality of synthetic data are paramount. It is essential that simulated data accurately reflects real-world conditions, addressing inherent biases and limitations.

Consequently, capturing real-world data (e.g., RF data) from live networks is essential. Properly labeled datasets are vital for effective model training, making the organization, management, and preprocessing of this data critical steps. Ensuring sufficient data volume is necessary to develop robust AI models capable of performing reliably in diverse scenarios.

7.1.2 – Evolving Testing and Validation Approaches

Traditional stimulus/response-based validation methods are insufficient for devices that include AI-based signal processing functionality at lower communication layers. Scenario-based, end-to-end testing is essential for evaluating AI models under specific conditions (e.g., collecting wireless channel state information, handovers, interference, mobility, etc.) to assess their performance.

Enhancing software-in-the-loop (SIL), model-in-the-loop (MIL), and hardware-in-the-loop (HIL) simulations with real-world conditions ensures model robustness. Additionally, cyber-physical testing, which combines virtual and physical elements, is key to validating AI models in dynamic environments.

While broadening testing and validation coverage without extending setup and test times, AI can be leveraged to identify relevant test cases and reduce unnecessary complexity. Effective test design and prioritization are crucial to balance thoroughness with efficiency.

The notion of Explainable AI may also influence the way that AI-based communication systems are built and tested. While testing and validation are meant to assure proper function of algorithms and systems, Explainable AI can help to gain trust in these systems from design already. Therefore, trustworthy design of AI-based communications algorithms and testing and validation go hand in hand and may influence each other.

7.1.3 – Hyper-Automation and Model Robustness

Assessing the AI's resilience to adversarial attacks is vital. These attacks intentionally manipulate inputs to provoke the AI to make mistakes. Robustness against such threats is essential for safe real-world deployment.

Furthermore, AI systems must demonstrate fault tolerance in the face of unexpected disruptions or failures within the communication environment, particularly during critical operations. This also incorporates scenarios that the AI was not trained for.

7.1.4 – Interoperability Testing

In scenarios with two-sided models, like channel state information (CSI)-feedback enhancement as discussed in 3GPP Release 18 and 19, interoperability testing between vendors becomes even more crucial. Therefore, the 3GPP test specification needs to ensure the compatibility between the encoder running in the mobile device (UE) and the decoder running at the BS (network, gNB). The definition of such test architectures, in the form of reference autoencoders, plays therefore a pivotal role and will lay foundation and establish a framework for testing of AI- and ML-based algorithms in a future 6G network.

7.1.5 – Energy Efficiency Considerations

As 6G aims for sustainability, energy efficiency becomes paramount. AI models must be energy-efficient without compromising performance and accuracy. During testing, we need to validate their efficiency metrics while maintaining functionality.

7.1.6 – Conclusion

In conclusion, addressing these challenges and adopting effective testing strategies will be instrumental in the successful integration of AI into wireless communication systems. Robust validation processes and a focus on efficiency and resilience will pave the way for AI to play a central role in the future of wireless technology.

7.2 – Phased Array Antennas: Challenges in Testing and Validation

Phased array antennas (PAAs) are at the forefront of next-generation wireless communication systems. These intelligent arrays allow precise beam steering, reduced interference, and increased range. However, testing and validating PAAs pose unique challenges, especially as we venture into higher frequencies and integrate tightly packed devices. In the next paragraph, we explore the complexities of calibrating beamformers, measuring beam characteristics, and addressing cost-effectiveness in Over-The-Air (OTA) testing.

As we move into higher frequency bands (such as FR3 and beyond), the behavior of PAAs becomes more complex. Challenges include increased path loss, atmospheric absorption, and interference. Additionally, at higher frequencies, tightly integrated devices under test (DUTs) often lack traditional probing points for conducted tests. Alternative OTA measurement techniques are necessary to assess performance without direct access to internal components. The following challenges arise from these circumstances.

Beamformer Calibration: Beamformers require precise calibration to ensure phase and amplitude alignment across all elements in the array. The calibration process depends on the specific beamformer design, considering factors like phase stability and gain.

Measuring Beam Characteristics: Traditional antenna characteristics (e.g., total radiated power, sensitivity, gain, directivity, and beam width) remain essential. Active components within antennas (including beamformers) introduce new challenges:

- Modulated measurements (EVM, OBW, ACLR) are needed, especially in the main lobe direction.
- Secondary emission measurements (SEM) and ACLR in directions outside the main lobe (to address interference).

Validating Beamforming Dynamics: Energy-efficient beam adaptivity relies on fast and accurate beamforming. Dynamic reference test scenarios must verify these adaptivity requirements.

Measurement Uncertainty: Positioning uncertainty and movement affect the quality of OTA measurements. Specifics of radiated propagation (e.g., chamber effects) introduce additional uncertainty.

Cost-Effectiveness: OTA gear is often expensive, particularly for accurate measurements or large DUTs so the up-front capital investment and ongoing maintenance costs add up. Additionally, mechanical movement in OTA measurements can be slow and resource intensive. New approaches to reduce the cost for this type of test are needed.

Large Antenna Panels: Base station vendors aim for large antenna panels (up to 2048 elements per polarization) in the 7–24 GHz range. Besides the construction methods for large panels which might be composed of smaller units or monolithic design), at these frequencies nearfield propagation zone considerations necessitate new OTA test approaches. Additionally, managing multiple simultaneous beams (isolation, beamforming, power consumption) is also critical for systems with many users and will need additional test functionality to verify the system.

7.3 – ISAC: A Paradigm Change in Testing and Validation

Communication (2G to 5G) and radar applications (as known e.g. in the automotive sector) have been studied, developed and commercialized separately until today. ISAC, also known as joint (or integrated) communication and sensing (JCAS/ICAS), uses reflections from communication signals to sense objects. Achievements in this field could enhance existing applications, for instance in the automotive and industrial applications, or create new use cases in data communication and environmental sensing (e.g., for surveillance, e-health, industrial or drone applications).

Sensing architectures: Multiple sensing architectures are possible, i.e., mono-static and bi-static sensing based on both BSs and/or user devices. In the mono-static case the sensing device (either the BS or the user device) transmits the ISAC signal and evaluates signal reflections for object detection. Calculation takes place at a single location without the need for data transfer between nodes. However, mono-static sensing requires full duplex operation, because transmitting and receiving is required at the same time. Existing communication systems use either different frequency bands or different time slots to separate transmit from receive, i.e., avoiding full duplex. Bi-static sensing can avoid FDD, as the ISAC signal is transmitted by one node (either BS or user device) and reflections are received by a different node (again either BS or user device). In this case the sensing node has limited knowledge about the transmitted signal, since large parts of the signal are used for communication. Consequently, object sensing can only be based on known signal parts and/or communication between nodes is required.

ISAC increases spectrum efficiency overall as communication and sensors utilize the same spectrum and signals are transmitted and received by potentially the same hardware. This in turn leads to opportunities and challenges from a testing perspective.

Testing challenges: Most importantly, verifying sensing performance adds a new set of KPIs to existing communication testing. Communication performance testing relies on well-established KPIs, e.g., from audio/voice quality or minimum data rate on application layer to physical layer characteristics like out of band emissions or minimum Error Vector Magnitude (EVM) measurements. These are usually determined by emulating or measuring the transmitter or the receiver side of a Device Under Test (DUT). In contrast sensing performance requires to qualify object parameters like distance, speed and potentially directional information, which are determined by the DUT based on signal reflections. Qualification of these results is done either based on real objects with known characteristics or by using test instruments, which emulate objects with reference characteristics. Using real objects comes with challenges as repeatability and reliability is time and cost consuming. Furthermore, the variety of test cases is limited, specifically considering a high number of objects at high speeds. Object emulation with test instrumentation enables reliable and repeatable testing covering a huge variety of scenarios, however the emulation of objects may not reflect all characteristics of a real object.

An additional challenge is the modeling of objects in combination with propagation characteristics. 3GPP has developed comprehensive channel models (refer to TR 38.901) reflecting real world propagation conditions, which enables efficient testing of communication performance. However, these models do not include dedicated objects, which are required for sensing verification. Comprehensive channel sounding measurements are required to determine object reflection characteristics in the spectrum of interest, which in turn will allow to develop appropriate channel models for testing.

7.4 – Testing Challenges Leveraging the Potential of (sub-) THz Spectrum

Unlocking the potential of the sub-THz and THz frequency regions (100 GHz to 3 THz) with the available extremely high bandwidths of several GHz represents a technological way forward. Besides ultra-high data rates in wire-less communications, this would also benefit sensing and imaging applications as well as possible future medical diagnostic procedures. Current research activities concentrate on two main frequency ranges from 90 to 170 GHz and above 300 GHz.

To fully exploit the THz potential for the development of future communications standards such as 6G, it is crucial to understand the propagation characteristics by performing channel measurements. The subsequent development of new channel models for these new communications frequency bands represents one of the first steps in the standardization process. Ultimately, these models serve as a basis for emulating corresponding propagation conditions in testing instruments to objectively verify performance limits of DUTs. The main challenge is to manage the tradeoff between sufficient accurate approximation of real-world propagation conditions and testing complexity.

The technical challenges of millimeter waves known from current 5G deployments are even more pronounced in the terahertz range. This includes higher path loss and shorter range. However, similar to millimeter waves, these problems can be mitigated by focusing the waves through beamforming. The shorter wavelengths have the advantage that more antennas can be fitted into a small package to produce highly pinpointed beams. However, contacting highly integrated Antenna in Package (AiP) devices becomes more demanding as reliable connections (e.g. waveguide) may not be available. Consequently, OTA measurements are of high importance, whereas calibration and precision in DUT placement are critical and require carefully and accurately designed testing setups.

7.5 – Testing of XR-Based Applications to Fully Enable the Metaverse

The current 5G specification presents challenges for delivering XR-based applications and services, as key features like low latency and power efficiency are distributed across multiple releases. Although these capabilities are evolving, with Releases 18 and 19 introducing more targeted functionalities, 5G still lacks the cohesive framework needed to fully support XR. The limitations of 5G underscore the importance of the advancements expected with 6G, where XR-based services and applications are poised to become a primary focus from the outset. To ensure the readiness of XR applications for the next generation of wireless communication, the need for comprehensive testing frameworks is paramount.

The vision for 6G is to establish XR as the consumer "killer application", driving the design and deployment of networks and devices. To achieve this, offloading computational tasks from devices to the cloud will be a critical enabler. This approach allows devices to handle demanding XR applications by leveraging the processing power of cloud servers, which can perform graphics rendering and other intensive tasks more efficiently than the limited hardware of mobile devices. However, this shift necessitates robust testing strategies that emphasize the optimization of latency and throughput. A key performance metric in this context is motion-to-render-to-photon (M2R2P) latency, which measures the delay between a user's movement and the corresponding visual update in the XR environment. Minimizing this latency is essential for maintaining user immersion and preventing motion sickness.

In 6G networks, XR devices will need to manage computational tasks based on real-time network conditions dynamically. This flexibility will involve shifting processing loads between the device and various server locations, whether in the central cloud, at the network edge, or within a local network. Such dynamic task allocation introduces complexity into the testing process, as traditional testing methods focused solely on air interface functionality will no longer suffice. Instead, test frameworks must be capable of emulating a range of network conditions and evaluating how these shifts in computation affect application performance. This approach necessitates a deeper understanding of the interplay between device capabilities, network infrastructure, and cloud computing resources, challenging us to push the boundaries of our knowledge and expertise in wireless communication. Therefore, comprehensive testing frameworks must account for these differences, ensuring that XR services perform consistently across various scenarios and configurations.

In addition to addressing the core network and computational challenges, the testing framework must also integrate new IP protocols designed to enhance network performance. One such protocol, Low Latency Low Loss Scalable Throughput (L4S), is particularly relevant for counteracting network congestion and optimizing latency in XR applications. Furthermore, modem APIs, OS-specific APIs, and network APIs play a crucial role in fine-tuning latency and throughput. By incorporating these protocols and APIs into the testing process, developers can ensure that XR services maintain high performance even under congested network conditions.

Testing XR applications also requires evaluating performance across a spectrum of use cases and environmental conditions. These scenarios include ideal, moderate, and harsh RF environments and varying network load levels, from no traffic to heavy congestion. By testing under these diverse conditions, developers can identify potential issues and optimize the application to perform reliably in real-world situations.

To achieve a truly immersive and reliable XR experience, testing must extend beyond individual components to encompass the entire E2E user experience. Quality of Experience (QoE) testing is a comprehensive approach that evaluates how all elements of the XR ecosystem—from network infrastructure to device hardware and software—work together to deliver the intended experience to the user. This holistic perspective is essential for identifying and addressing potential issues that could detract from the user's experience. Industry efforts to standardize XR QoE measurement will play a pivotal role in shaping future testing frameworks, emphasizing the need for collaboration and alignment in the industry.

In summary, the transition from 5G to 6G represents a significant evolution in the testing and deployment of XR-based applications. The focus on XR as a central use case in 6G will drive the need for advanced testing frameworks that can address the unique challenges posed by dynamic task allocation, diverse network conditions, and the integration of new protocols. By adopting a comprehensive E2E approach to QoE testing and staying aligned with industry standardization efforts, developers can ensure that XR applications are ready to fully enable the Metaverse, delivering the immersive and seamless experiences that users demand.

7.6 – Conclusion

In conclusion, the journey towards 6G presents a myriad of testing, measurement and validation challenges that span across various advanced technologies. From the complexities of AI and phased antenna arrays to the integration of sensing and communication, sub-THz frequencies, and XR-based applications, each domain requires meticulous testing to ensure reliability, performance, and security. By addressing these challenges with innovative testing methodologies, we can pave the way for the successful deployment of 6G, unlocking its full potential and transforming the future of wireless communication.

8 – Conclusion

This white paper aims to provide an extensive roadmap for and insights from the evolution of telecommunications, with 6G as a transformative force across different sectors. It analyzes several new use cases that will potentially leverage emerging technologies and advancements within the 6G ecosystem to enhance safety, efficiency, and resilience in society. By examining common themes and intersections among these use cases, the white paper identifies eight primary use case families (UCFs) that represent key application areas for the upcoming 6G era. These areas span several transformative advancements, such as advanced robotics, global environmental monitoring, ubiquitous connectivity, holographic communication, airspace mobility, and more.

The identified UCFs highlight the emerging technological building blocks (TBB) of 6G, as well as the challenging application requirements that 6G must address. Further categorization of the TBBs aims to align development priorities with real-world applications and anticipated technological needs. The analysis of the 29 TBBs under three development stages provides a structured roadmap for the prioritization of essential and advanced technologies. Moreover, the analysis of 6G features and requirements shows that 6G use cases put a strong emphasis on trustworthiness features, improved network capabilities for reliable low-latency communication, and more flexibility offered by the network infrastructure.

The white paper also discusses selected testing and measurement challenges that arise when the aforementioned TBBs will become part of new 6G communication systems under the specified requirements. The introduction of AI and more complex algorithms call for enhanced test approaches in need for new innovative test solutions.

In summary, the 6G Platform envisions in this white paper a paradigm shift in connectivity, combining technological advancement with societal goals of resilience, sustainability, and trustworthiness. As stakeholders move forward, a collaborative approach, rooted in rigorous testing, regulatory harmonization, and continuous innovation, will be essential. This strategy will ensure that 6G realizes its full potential as a foundational element of the future digital landscape, empowering industries, enhancing daily life, and fostering a globally connected ecosystem.

Abbreviations

3DM	3D Mobility
3GPP	3rd Generation Partnership Project
6G AI	Industry Association
6G-SNS	6G Smart Networks and Services
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AIaaS	AI as a Service
AMR	Autonomous Mobile Robots
AR	Augmented Reality
BS	Base Station
CR	Collaborative Robots
DT	Digital Twin
DUT	Device(s) Under Test
EA	Environmental Awareness
E/E	Electrical/Electronic
E2E	End-to-End
ECU	Electronic Control Unit
ERP	Enterprise Resource Planning
eMBB	enhanced Mobile Broadband
EMS	Electrified Monorail System
ETSI	European Telecommunication Standards Institute
EU	European Union
EVM	Error Vector Magnitude
FCW	Fully-Connected World
GDPR	General Data Protection Regulation
gNB	Next Generation Node B
GSMA	GSM Association
HAPS	High-Altitude Platform Station
HIL	Hardware-in-the-loop
HMO	Head-Mounted Displays
ICU	Intensive Care Unit
ICE	Intercity Express
IE	Immersive Experience
IoT	Internet of Things
ISAC	Integrated Sensing and Communication
ISO	International Organization for Standardization
ITU	International Telecommunication Union

JCAS	Joint Communication and Sensing (mostly equals ISAC)
KPI	Key Performance Indicator
L4S	Low Latency Low Loss Scalable
LAPS	Low-Altitude Platform Station
MEC	Multi-access Edge Computing
MIL	Model-in-the-loop
ML	Machine Learning
MIMO	Multiple Input Multiple Output
MLOps	Machine Learning Operations
MNO	Mobile Network Operator
NaaS	Network as a Service
NEF	Network Exposure Function
NFVI	Network Function Virtualization Infrastructure
NGMN	Next Generation Mobile Networks Alliance
NPN	Non-Public Networks
NTN	Non-Terrestrial Networks
O-RAN	Open Radio Access Network
OTA	Over-The-Air
PAA	Phased Array Antennas
PQC	Post-Quantum Cryptography
pRRM	proactive Radio Resource Management
QKD	Quantum Key Distribution
QoS	Quality of Service
QRNG	Quantum Random Number Generator
R&D	Research & Development
RAN	Radio Access Network
REM	Radio Environment Map
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surfaces
RS	Resilient Society
SAR	Synthetic Aperture Radar
SCADA	Supervisory Control and Data Acquisition
SDO	Standard Development Organizations
SEM	Secondary Emission Measurements
SIL	Software-in-the-loop
SLA	Service Level Agreement
SME	Small and Medium Enterprises
TBB	Technical Building Blocks
TCEP	Time-Correlated Entangled Photon-based Synchronization
TE	Trustworthy Environment
TN	Terrestrial Networks

TSN	Time-Sensitive Networking
UAV	Unmanned Aerial Vehicle
UC	Use Case
UCF	Use Case Family
UPF	User Plane Function
URLLC	Ultra-Reliability and Low Latency Communication
UE	User Equipment
UTM	Universal Transverse Mercator
VLC	Visible Light Communications
VR	Virtual Reality
XR	Extended Reality

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Appendix

A.1 - Definition of Technology Building Blocks

Seven main categories as well as a total of 29 TBBs have been defined (refer to Table 1) and are described in detail in the following:

(A) Integrative AI solutions for network and application enhancement

Integrative AI solutions for network and application enhancement encompass a range of technologies and strategies specifically relevant within the context of 6G development. These solutions aim to leverage AI to optimize the performance and functionality of 6G networks and applications. By integrating AI into various aspects of network and application management, the objective is to enhance efficiency, reliability, and overall user experience. The processing can certainly happen at the edge or in a cloud, as described in section E. Reference is made to the layer concept, which consists of the following layers: Application Layer, Infrastructure Layer, Security Layer, Management and Orchestration Layer, and Service Layer.

(A1) AI in Infrastructure

In the context of the 6G mobile telecommunications era, the deployment of AI will transform the infrastructure layer. AI enables dynamic management of network infrastructure by automatically adjusting resource allocation and optimizing network load in real-time. This enhances both the efficiency and reliability of the network. Specific AI technologies employed include predictive analytics for proactive capacity adjustment, automated error correction through deep learning, and cognitive radio for dynamic frequency selection. The infrastructure layer, comprising BSs, data processing centers, and core network elements, is optimized through AI. AI applications in edge computing support latency-critical services such as autonomous vehicle control, while network slicing creates virtual networks tailored to specific service requirements. Additionally, AI improves the energy management of infrastructure components, which is crucial during peak times. With the advanced implementation of AI technologies, the 6G network is expected to become not only more efficient but also more adaptive and future-proof.

(A2) AI in Network Management and Orchestration

In the 6G mobile communication generation, AI is expected to play a central role in data management and orchestration. AI technologies enable advanced analysis and processing of large volumes of data generated within 6G networks. Through ML, networks become self-learning, enabling them to recognize traffic patterns, dynamically allocate resources, and predict and prevent network failures. Specifically, AI/ML-based parameter estimation allows for more precise adjustments of network settings based on real-time data analysis. Additionally, the integration of an AI-driven RAN controller enhances automation in the RAN, significantly improving the network's efficiency and responsiveness. The integration of AI also promotes automation in service orchestration, facilitating the rapid and efficient delivery of network services. This is particularly important for supporting technologies such as the IoT and autonomous systems, which require extremely low latency and high reliability. Thus, AI reshapes data management and orchestration in 6G by enabling smarter, more responsive, and self-optimizing network functions.

(A3) AI in the Service Layer

Under "AI in the Service Layer" in the context of 6G mobile communications, the integration of AI focuses on optimizing service management. AI technologies enable advanced automation and intelligent decision-making in the service layer, contributing to the efficient provision and management of various network services. Through the use of ML and deep analytics, the network can dynamically respond to changes, allocate resources optimally, and improve QoS for end users. AI-driven orchestration in the service layer also allows for more precise utilization of network slicing to meet specific requirements of various applications. This includes real-time data analysis and proactive management, essential for enhancing efficiency, scalability, and security in 6G networks, ensuring a seamless user experience. Additionally, AI as a Service (AIaaS) and Machine Learning Operations (MLOps) play important roles in the context of "AI in the Service Layer." AIaaS provides AI functionalities and models as a service, facilitating access to advanced AI algorithms for service providers. MLOps refers to the operationalization of ML, enabling efficient development, implementation, monitoring, and management of ML models. In the context of the service layer, AIaaS and MLOps support the integration of AI by providing infrastructure and tools for the development and operation of AI-driven services, further enhancing efficiency and scalability.

(A4) AI in Advanced Technologies and Applications

The development of the 6th generation of mobile communication is characterized by the integration of advanced technologies and applications. The use of AI significantly enhances the function and performance of these technologies. Edge computing and distributed clouds are employed to bring data processing closer to the end user, minimizing latency and maximizing the efficiency of real-time applications. In the realm of immersive technologies, VR, AR, and XR enable enhanced and more realistic user experiences through the use of AI. These technologies benefit from improved image processing and user-driven adjustments made possible by AI. Autonomous vehicles and intelligent transportation systems utilize AI to optimize traffic control and increase safety through more precise environmental perception and faster decision-making. The IoT is empowered by AI to operate more efficiently, employing adaptive algorithms to make devices smarter and automate their interaction. Another area is holographic communication, which leverages advanced codecs to efficiently transmit three-dimensional images in a lifelike manner, profoundly altering communication systems. AI is used primarily for the interactive elements of this technology. Additionally, haptic feedback technology, in combination with AI, enables physical feedback in VRs and ARs, enhancing immersion by simulating tangible real-time responses, which can be crucial for applications ranging from remote medical care to interactive learning environments. Together, these technologies form the foundation for the transformative power of 6G.

(A5) Digital Twin, Simulation, and Data Fusion

In the context of 6G technology, the integration of digital twins, simulation, and data fusion enables the remote management of systems and physical assets. A digital twin is a detailed model that captures the real-time and historical state of a physical asset, functioning independently from its physical location. This model, connected through networked sensors, enhances operational efficiency through predictive simulations and optimizations. AI plays a crucial role in data fusion and simulation. The integration of diverse data sources through AI-driven data fusion improves the accuracy of the digital twin and enables precise simulations. Furthermore, AI automates the generation and analysis of these models, facilitating complex scenario analyses that support real-time operational adjustments and enhance network security. The integration of the digital twin concept across all network layers—application, service, management, orchestration, and security—

creates robust interconnections between various applications, significantly bolstering network resilience and performance. The integration of AI into the 6G network not only enhances its efficiency but also facilitates greater adaptability and security. Due to security requirements and the required QoS of the network, this TBB links to G3 and D4.

(B) Comprehensive Network Systems and Services

The TBB "Comprehensive Network Systems and Services" highlights developments in network technology that aim for a modular and service-oriented architecture composed of physical elements and software-based microservice functions. This architecture is intended to significantly enhance the adaptability and scalability of network services. Through the implementation of flexible orchestration and dynamic placement of network functions virtualized within a cloud continuum, 6G meets the demands for low latency and high reliability. This approach enables the deployment of functions and services on demand, thereby forming the basis for a continuous evolution of network systems rather than relying on iterative technological revolutions. This modular structure supports more specific and demanding applications and services, making 6G a key technology for future communication requirements.

(B1) Network Infrastructure and Technology

This section covers network functions and physical resources of the infrastructure to accommodate RAN, Core, security, data, and AI/ML functions in a 6G network. This includes cloud-native virtualization frameworks (e.g., NFVI), transport links, and non-terrestrial infrastructure. Key building blocks will enable SLA-aware device-to-device and device-to-service communication across networks, even when crossing different operators' domains. This will involve control mechanisms to communicate and allocate required network resources. 6G needs a modular architecture that can grow and adapt based on current needs. Network modularity aims to decompose the 6G system into orthogonal building blocks (i.e., network functions, services, and interfaces) that can change dynamically. Networks are modularized into microservices, running in a cloud continuum owned by different operators, federating across boundaries. However, Hexa-X-II proposes to streamline 5G service-based NFs to reduce failure points, processing occasions, and latency. Optimized network function interfaces will simplify inter-module interactions with an E2E vision. NFs in 6G are expected to be virtualized and flexibly orchestrated, with the capability for runtime optimization and dynamic placement. Previously, RAN and core networks were separately specified. Hexa-X-II proposes optimizations and flexible localization in a cloud continuum along the mobile communication system's delivery chain.

From today's perspective, this will require Network Function Virtualization Infrastructure (NFVI) across the entire delivery chain, with flexible feature development and runtime deployment. The 5G system consists of a modular, service-based user and control plane, where the UPF (user plane function) handles user traffic as a monolithic element. In 6G, UPFs will be tailored to the specific needs of the intended application.

Network slicing groups network functions that meet the SLA needs of specific applications or tenants, deploying them at the most appropriate locations. Networks are logically separated from their physical resources, and slices can be flexibly deployed, scaled up or down in real-time. Another important topic regarding network infrastructure is network topology, especially the RAN. To enable advanced transmission technologies like Cooperative Multipoint Transmission or Cell-free Massive MIMO, a new flexible topology is necessary. This includes a redesigned fronthaul and distributed architecture.

(B2) Network Management and Optimization

This TBB comprises all technologies and functions focusing on the management and optimization of the network. These follow from the envisioned structure of 6G as a more modular basket of features. That is, in operation, it will be rather a fluid ensemble of services as opposed to strictly separated monoliths of Core and RAN. While this requires a more flexible orchestration and underlying platform for interaction (as mentioned below in G), this enables new capabilities regarding system composition, feature development and system lifecycle. Services can be deployed across the physical network, new features added in and where required scaled to adapt to changing demands on-the-fly while maintaining end-to-end compatibility of communication services. For future systems, this also means a continuous evolution instead of iterative revolutions, in the sense that a system's capabilities develop over time and can change according to requirements. End to end network, service management and orchestration are mandatory in 6G. Observability shall be enabled by processing of telemetry data in data fusion fabrics assisted by knowledge-based models and closed loop coordination. However, as the current models only describe how networks of single operators can be operated, for E2E management the networks have to cooperate in order to monitor SLA and user experience alongside the whole data path of user traffic.

(B3) Network Types and Configurations

This subcategory addresses technologies that enable the highly flexible configuration of networks within the 'network of networks' paradigm. This includes resource allocation algorithms between different networks.

In 6G-related use cases, such as automated factories with cooperating AGVs, multiple networks will coexist. For example, AGV communication requires a URLLC network with low-cost transmitters and receivers in direct device-to-device mode. In contrast, AGV-to-infrastructure (X2I) communication will require an eMBB communication network.

(B4) Cell-Free Architecture

The "Cell-Free Architecture" TBB includes functionalities necessary for implementing networks using this approach. Unlike traditional cell-based structures, in a cell-free architecture, UEs are no longer rigidly linked to a specific BS. Instead, they can connect to multiple BSs simultaneously, allowing parallel data routing. This also enables device-to-device communication without a BS intermediary, forming the basis for distributed JCAS/ISAC systems. This technology is highlighted as a separate TBB due to its significance to the 6G architecture but remains heavily linked with B3.

(B5) Service Models and Access

6G aims to provide comprehensive coverage and services tailored to specific, usage-based QoS requirements. These services will be managed end-to-end across multiple operators. This subcategory encompasses technologies that integrate and interconnect access networks of different operators and NTNs, such as satellite networks. This includes unified subscription standards and interference control technologies between TNs and NTNs. Additionally, use cases like holographic communication, which have specific QoS requirements, will require service differentiation technologies.

(B6) Interfaces for Advanced Technologies and Applications

This TBB includes required functionalities providing network-centric functions in infrastructure and exposure APIs within a 6G network. Services like voice and video communication, VR, messaging, and JCAS/ISAC will need specialized frameworks for infrastructure and application layers. Each will expose capabilities on both the northbound to applications and on the east-west level between operators. AI as a Service and Digital Twin technologies will also be integral to 6G.

(C) Advanced Network Architectures and Connectivity Solutions

Advanced Network Architectures and Connectivity encompass all technologies that aim to provide a flexible network architecture and seamless interoperation between different networks. This includes the joint operation of terrestrial, non-terrestrial, and various types of TNs like 5G and nomadic networks. The high flexibility of the infrastructure enables dynamic network adaptation to changing conditions and supports advanced services like network slicing.

(C1) Integrated Network Technologies

Integrated Network Technologies comprises all technologies for the operation and seamless connection of TN and NTNs. In the case of terrestrial mobile networks, this includes technological advancements of the existing stationary 5G infrastructure and new network types within the 6G framework, e.g., nomadic networks, campus, and non-public networks. In the case of Non-Terrestrial Networks, this means satellite-based and HAPS networks.

(C2) Adaptive Network Infrastructure

The subcategory "Adaptive Network Infrastructure" refers to flexible network architectures that can adapt to changing requirements. This includes spatially distributed Radio Access (RA) infrastructure, which is designed to ensure uniform network coverage over large areas. This can be achieved through distributed transmission stations that guarantee efficient network utilization and high availability, even in densely populated areas. Furthermore, multi-tier networks and dynamic subnetworks play a crucial role in responding to varying densities of UEs. This means that the network is capable of automatically restructuring itself and dynamically allocating resources depending on the number of devices active in a particular area. These adaptive infrastructures are essential to meet the high demands for flexibility and scalability of 6G networks and to ensure seamless connectivity in an ever-changing environment.

(C3) Network Services and Configurations

The category "Network Services and Configurations" includes the technical building blocks necessary for the realization of customized network services and the enhancement of data transmission. The technologies include network slicing, which allows the division of a physical network into multiple virtual networks, enabling individually tailored services for various use cases. This enables efficient use of network resources and improved service quality. Additionally, this category encompasses semantic communication and Time-Sensitive Networking (TSN), which are designed for reliable and time-critical data transmission. Semantic communication aims to maximize the relevance of transmitted data by conveying only meaningful information. TSN ensures precise temporal coordination within the network to meet the requirements of applications with high latency sensitivity. These components are essential to boost the performance and efficiency of 6G networks in view of the diverse and demanding communication needs.

(D) Converged Network Systems and Advanced Communication Technologies

Converged Network Systems and Advanced Communication Technologies concentrate on beyond-communication functionalities that will appear in the context of 6G. These follow from the technological advancement towards (1) higher frequencies and larger bandwidths, (2) integration of intrinsic computational capabilities within the network, and (3) Quantum technologies. From these points, it follows that a 6G system converges towards and merges with previously separated technologies, most prominently Radar sensing with JCAS. These technological advances also include capabilities that facilitate the application-driven adjustment of the network to provide service excellence.

(D1) Joint Communications and Sensing

JCAS, also known as ISAC comprises technologies that aim at using the telecommunication infrastructure in parallel for radio sensing of the environment. The term radio sensing covers both radar-sensing and spectral sensing. Due to the non-cooperative nature of the objects of interest, JCAS/ISAC includes steps for object detection, separation, tracking and classification in addition to estimation. This sets this TBB apart from D2, which only involves an estimation problem. Due to the multitude of tasks included in this TBB, it is distributed over all layers – infrastructure, network service, and application. The respective radio hardware, typically as part of a base station, possibly including a sniffer radio unit for a (quasi) full duplex, mono and/or multi-static operation, is on the infrastructure layer; protocols that control the operation, including allocation and coordination of resources for (bi-static or multi-static) sensing, are connected to the network service layer; and algorithms for data assessment (distributed or centralized) operate on the application layer.

Connecting algorithms on the network service layer, which control the operation, and the hardware on the infrastructure layer, makes the special operation of the system like in terms of SAR (the creation of small beams for imaging) feasible. In conjunction with other TBBs, e.g., A2 or B2, JCAS/ISAC can be used to improve or optimize the functionalities of RAN. While the communication-centric operation is in the focus, this TBB also extends to radar-centric operations, by extending radar systems with necessary functionalities to connect to the network. Due to security and trust requirements, this TBB links to G3. Furthermore, through the extension of network operation, TBB categories A (A2) and B (B1 – B3) are connected to JCAS/ISAC operations.

(D2) Sensing, Positioning, and Time Synchronization

Sensing, Positioning, and Time Synchronization comprises all technologies that aim at localizing devices within the network, e.g., cooperative objects. Since the objects are known to the system, the sensing task consists only of an estimation problem. As positioning requires spatial and temporal information of the device (location of device at given time), the necessary technologies are hardware and/or protocols for the distribution and acquisition of timing information, i.e., time synchronization, thereby involving the infrastructure and network service layer. This hence includes specifications (data formats) for the distribution of common spatial and temporal information (sensor & clock data). This aspect of time synchronization connects with the aspect of TSN of C3. Together with the information generated by D1, this TBB provides functionalities for applications like Simultaneous Localization and Mapping or XR (computational offloading for XR in D4).

(D3) Quantum Technologies for Network Infrastructure

The TBB of Quantum Technologies and Network Infrastructure comprises all quantum-based technologies supporting the high-performance operation of or within the network. Examples include highly accurate clock synchronization using quantum entanglement or QKD for secure communications. Quantum computing promises to solve complex computational problems encountered in the planning and operation of telecommunication networks. Besides, quantum communication is discussed, which is traditionally based on quantum repeaters and teleportation and requires the generation and detection of single photons.

(D4) Interoperability and Service Excellence

Interoperability and Service Excellence comprises all technologies that aim to manage and balance the different requirements of the UE on the network within an area – possibly heterogeneous tasks based on the individual application, e.g., data for XR, JCAS, V2X, etc. On the level of the single system (e.g., base station), this means spectrum sensing and management. On the level of the networked system, this means interference mitigation, network slicing, and operations for ensuring resilience of the service. On the application level, this means, among others, offloading of non-time-critical computations, application-driven and device-driven optimization for Beyond Communication Services, but also providing trustworthy APIs for the connection of, e.g., Digital Twins.

(E) Integrated Cloud-Edge Ecosystem Transformation

TBB Integrated Cloud-Edge Ecosystem Transformation comprises various computing solutions (edge, cloud, fog) to elaborate data processing, storage techniques, and computing architectures and technologies.

(E1) Edge Computing Innovation

Edge computing is a data processing paradigm that involves the processing and storage of data at the source of its generation, rather than relying on centralized data centers. This decentralized approach brings computing and data storage closer to users, devices, and sensors that generate and consume data. By processing data locally at the network edge, edge computing reduces latency, enhances real-time capabilities, increases bandwidth efficiency, and improves data privacy and security. Similarly, fog computing is a distributed data processing paradigm that aims to bring computing resources closer to the data source. While edge computing focuses on processing data as close as possible to its origin, fog computing extends this concept by introducing an intermediate layer between edge devices and the central cloud. Fog computing nodes, positioned closer to edge devices, enable more comprehensive data management from multiple sources and more efficient resource utilization across the network. Future 6G networks will consider computing capacities across the entire network, from the farthest edge, including the end device, to Telco Grade Clouds (CC, Compute Continuum). These networks will also support various types of offloading, including partial or complete offloading, to facilitate the remote execution of applications within the cloud. This will not only enhance the scalability of edge and fog computing solutions but also allow for more flexible and efficient use of network resources, thereby increasing the performance and adaptability of the entire system.

(E2) Computing Architectures and Technologies

Edge computing architecture encompasses a decentralized framework designed to process data and execute applications closer to the source of data generation. At its core, edge computing architecture consists of three main components: edge devices, edge computing nodes, and centralized cloud infrastructure. Edge devices, such as sensors, actuators, and IoT devices, are responsible for collecting data from the physical environment. Edge computing nodes, located at the edge of the network, perform data processing, analysis, and storage tasks, enabling real-time decision-making and local computation. The centralized cloud infrastructure serves as a repository for storing historical data, providing additional processing power, and facilitating coordination between edge devices and computing nodes. This architecture enables distributed computing capabilities, allowing organizations to leverage edge resources efficiently while maintaining connectivity to centralized cloud services for scalability and coordination across the network. Orchestration serves to enhance the coordination and management of distributed resources, ensuring efficient resource utilization and seamless interaction between local processing and the central cloud. The network supports this architectural framework through robust connectivity and network services, which facilitate efficient data transmission among components and provide critical network functions such as dynamic bandwidth allocation and low-latency transmission. These elements are crucial for the performance and security of edge computing within a 6G network.

(F) Air Interface

This TBB category summarizes all TBBs closely linked to the physical and MAC layer and, therefore, to the hardware used. We see a great need for intelligent antenna systems and transceiver architectures, which are mandatory for future (fully) integrated JCAS systems. Subcategories representing the TBBs from the collected use cases are defined below.

(F1) Spectrum

Sufficient spectrum is required to enable high data rate for communications or high range resolution for sensing. These spectra must be allocated in frequency ranges that smartphone devices can access and use. This results in a demand for frequencies and spectrum for IoT use in Ku/a bands. Or flexible spectrum assignment is aimed for, for example, by assigning terrestrial spectra. In 6G, we assume different frequency ranges will be available and use cases can individually select the best fitting frequency. However, usage rights are an influencing factor and are subject to national regulations. Currently, the three frequency ranges (FR1, FR2, and FR3) are in focus.

- (F1.1) FR1 (410 MHz to 7125 MHz)
- (F1.2) FR2 (24.25 GHz to 71.0 GHz)
- (F1.3) FR3 (7.125 GHz to 24.25 GHz)
- (F1.4) FR THz (92 GHz to 174.8 GHz)
- (F1.5) FR THz (>300 GHz)

(F2) Flexible Antenna Structures and Arrays

This TBB encompasses flexible antennas for BSs and UEs. Flexibility is seen in terms of flexible structures and flexibility in the use of spectrum. Mechanical flexible structures or LCD antennas are examples of flexible structures. In contrast, multi-band antennas enable, e.g., the support of a greater number of independent streams and link distances in dynamic scenarios while simultaneously operating in various frequency bands, which is linked to categories (F4) and (F5).

(F3) Multi-Antenna Beamforming and Beam Management

Multi-antenna beamforming and beam management encompass the need for advanced antenna technologies. With the transition to higher carrier frequencies, the need for novel beam management (e.g., AI-controlled beam management) is increasing, especially for frequencies in the mmWave and sub-THz range. In this context, there is an expected need to implement Phased Arrays: (physical/electronic) beam-steering for focusing the beam to the area of interest as the beams will get more and more narrow. A special issue is joint transmit/receive beam management, which will be different from pure communications. This will become especially true regarding radio surveillance systems where, e.g., infrastructure-centric NTN-ISAC is considered. It relaxes if a radar sniffer can be located as a sensor close to the target in the same footprint as the illuminator.

(F4) Advanced Transceiver Technologies

Advanced Transceivers comprise all technologies needed to keep pace with the increase in carrier frequencies and bandwidths. This TBB is assigned to cover the transceiver part after the physical antenna and a potential beamforming structure. Semiconductor technologies, amplifier structures, filter(-banks), etc., have been developed and are still under consideration to make the front-ends suitable for mmWave/sub-THz frequency bands. Besides, advanced technologies reflect support for full-duplex mode as well as, for example, mechanical flexible structures and the needed underlying (semiconductor) materials. In addition to supporting mmWave signals, advanced transceivers must also enable support for multiple radio technologies, including (digital) adaptive structures that will allow different waveforms, e.g., for JCAS or heterogeneous networks. This includes energy-efficient and high-speed signal processing algorithms and hardware for processing ultrawideband baseband signals for mmWave/sub-THz systems.

(F5) Reconfigurable Intelligent Surfaces

This category comprises the physical and MAC layer aspects of reconfigurable intelligent surfaces (RIS), corresponding to programmable surface structures built to control the reflection of electromagnetic waves by changing their electrical and magnetic properties. Strategically placing such structures in the radio channel between a transmitter and a receiver makes it possible to control how the signals are propagated in the wireless channel. Thus, reconfigurable intelligent surfaces can direct signals to receivers, resulting in better reception or connection quality.

(F6) Cell-Free Massive MIMO

Another technology that has attracted considerable attention as a candidate for 6G is cell-free massive MIMO. In contrast to the classical massive MIMO approach, where multiple antennas are located at a single BS, in cell-free massive MIMO, single-antenna access points are distributed over the area to be covered. Each user is served by multiple access points simultaneously. By using proper precoding and power allocation algorithms, the performance of the network can be improved compared with conventional massive MIMO systems. The cell-free structure imposes new requirements on the network structure, especially on the fronthaul network. This TBB connects to (B4), Cell-Free Architecture.

(G) Orchestration and Management

Orchestration and management represent a fundamental building block of 6G. Their purpose is to enable the automated configuration of services and networks, as well as the closed-loop SLA monitoring that is necessary for the effective management of these resources. The orchestration and management capabilities will enable the specific deployment of services to users or groups of users, as well as the creation of "network slices" across the technical delivery chain, from user A to user B or a server.

(G1) Cross-Layer/Cross-Operator Interface for Service Control and Management Data and Information

In the contemporary telecommunications sector, individual network operators extensively manage their network elements, including configuration, monitoring, and troubleshooting. These networks are structured into specific areas, such as access, core, service, and transport networks. In order to provide specific service level agreements (SLAs) for end-user services, operators must implement precise configurations for each element within these network domains. This process is known as cross-domain orchestration. Consequently, end-users experience the SLAs within the network of a particular operator. In accordance with GSMA naming conventions, a specific SLA must be realized using a "Slice," with the conversion of an SLA into a Slice precisely defined in the GSMA document NG.116, the Generic Network Slice Template. However, a challenge arises in activating an SLA for end-users across multiple network operators, especially when end-user A is connected to network AA and end-user B to network BB. In order to achieve an SLA from A to B, all involved network operators along the data path must configure their network elements accordingly. In a recent study conducted by 6G LEGO, an analysis on this topic emphasized the ongoing relevance of Network Slices. Consequently, we propose that network operators must exchange information on SLA templates, namely Slice templates with defined values. Additionally, the immediate ordering and activation of private Slices/SLAs on demand should be facilitated. We also recommend the development of frameworks that include a data model, architecture, and modular interconnection. Such a framework would encompass E2E context-awareness management, enabling the network to optimize the E2E connection that spans eve component of network services and infrastructure, from applications through Edge Computing, RAN, Core Network (CN), to transport. Depending on the context, a fully or nearly deterministic network segment could be established.

Future network automation should extend the automation of network management and orchestration functions and follow the concept of element softwareization, Continuous Integration/Continuous Deployment (CI/CD) and AIOps frameworks, and intent-based management. These measures would enable more efficient, modular, and flexible support for network functions, thus enhancing the performance and adaptability of the entire system.

(G2) Enabling Interface and Templates for SLA Requests between Network Operators alongside the Technology Deliverable Chain

A brief summary of the preceding discussion is as follows: In the context of 5G, the NEF serves as a gateway or interface between the network infrastructure and external entities. It provides a standardized and secure method for authorized third-party applications to access network services, including connectivity, QoS control, policy enforcement, and subscriber data.
As of the present date, the NEF serves as a functional module, interfacing operators' core network service control and requesting specific capabilities. It is possible to define SLAs in a precise manner with the assistance of slice templates, as was previously discussed in TBB (G1). It is recommended that research be conducted into interfaces and methods for exchanging SLA templates between operators, with the objective of enabling automated and instantaneous transactions. Additionally, it is recommended that SLA templates be developed that contain 6G-related SLA attributes. In order to extend the home, private, or office network, it may be necessary to interface smaller networks that are not operator-driven. This is particularly the case

for 3D gaming, AR/VR on the shop or factory floor, which are use cases that traverse public networks, include non-public networks, and require high determinism.

The necessity of conducting research on the business interface between the end-user and the network/service operator that consumes the end-user resources is raised by the issue of inter-domain network management. It is also necessary to consider the possibility of a further business interface between operators, whereby their resources are added dynamically or periodically to the cloud continuum.

(G3) Security and Trust

The forthcoming 6G networks will be equipped with security and trust capabilities that can be accessed on demand. These capabilities will be made available to end users, applications, and operators. Security is to be regarded as a distinct entity within the overall architectural framework. It is necessary to differentiate between the built-in security measures in single network elements or functions and the capabilities. These capabilities will be accessible via application programming interfaces (APIs) by applications on the top or inside the user's device and also by other operators, for example, when interconnecting or providing roaming services. Consequently, 6G networks comprise a security plane analogous to the data (user) plane, thereby satisfying the security service demands of end users. This security plane provides security services to the service and application layers, automatically optimizes security policies and functions from the network function layer, and for the resource layer of the underlying infrastructure. The concept of trust and security will become a central tenet of 6G, with the security plane designed to execute security decision-making based on analytics, deductive reasoning, and exposure of capabilities. Secondly, the security plane controls capabilities, scheduling, collaboration, and policy control. Finally, security capabilities will be integrated into any element, function, or microservice, thereby providing trust and safety-enabling units. The integration of native capabilities into the network infrastructure enhances the network's resilience to potential threats, particularly in the domains of data, facility, and business security. These capabilities, which include blockchain, key management, and trusted computing, facilitate the implementation of trust-enabling units.

The provision of on-demand services necessitates the network's capacity to accommodate flexible combinations of functions and resources on the control and user planes. This implies that security must be integrated throughout the entire lifecycle of 6G networks and the wireless communication layer. To achieve this, security must be integrated with network capabilities.

At the level of architectural elements, Confidential Computing represents a key component of confidential network deployment, which enables the establishment of trust relationships between service providers and their tenants. In a data-driven 6G system, trustworthy AI plays a pivotal role in ensuring the security and privacy of the data. The establishment of trust infrastructures will be facilitated by the implementation of trust level agreements (TLAs) and key value indicators (KVIs) between the relevant parties. To satisfy the requirements of quantum proofness and cloud awareness, it will be necessary to implement physical layer security enablers such as evolved cryptography. Context awareness offers methods to adapt controls in a manner that is appropriate to the situation. One potential solution to the issue of information storage and the protection of data is the use of distributed ledgers. A network digital twin, which contains the same elements of the real environment, is used to generate data evidence. Digital twins can be employed to anticipate potential downtime, react to changes, test designs, and evaluate security threats and mitigation strategies. AIML must be implemented to prevent the emergence of unforeseen risks and to detect anomalies and deception at the physical layer.

A.2 - Feature Definitions in the Survey on Requirements

Architecture Category

Multi-connectivity IoT nodes

Given the capability of nodes in a 6G network to have connectivity to multiple other nodes or to change connectivity among several nodes, network management must handle those multiple connectivity relationships and provide all management functions towards this situation.

Traffic steering / traffic control

Network Management shall be able to handle traffic in most efficient manner within the network considering all options the network can provide regarding routing, capacity provision, prioritization, etc. To allow best performance it might recognize services with their associated performance KPIs and allocate according to network resources – if available – to those services or prioritize those according to demands.

Allow network changes

Network Management shall apply Self Organization of the network to enable a fast and efficient operation and adaptation of the network to any changes in the network or to framework conditions.

Example:

A High-Altitude Platform enters the system and creates a new node.

- Of course, no manual changes by the operator should be required but the node should be automatically integrated.
- Given the new node in the network: What is now the best routing for any kind of traffic.

Self-healing network

Self-healing is the ability of the network of automatically disable a broken link and reroute the data to a different path.

If your answer is yes, please also indicate where self-healing is important:

Implications/Requirements

- for the application server
- for the network
- for the device

Network of networks

Network of networks denotes a system composed of multiple individual networks. Each network within an NoN operates independently but is interconnected with others to enable communication and collaboration. NoNs facilitate seamless data exchange and resource sharing between disparate networks, enhancing connectivity and interoperability. Each network offers different types of services (eMBB, URLLC) or even different radio access technologies (5G, WiFi, VLC, etc).

Holistic 3D network

A holistic 3D network is a network that has terrestrial and non-terrestrial nodes that are considered in a uniform matter to provide additional network capacity temporarily and locally as needed.

High autonomy level

For robotic systems, or more generally any autonomous machine system, communication is the key feature to not only communicate but also interact with the world around it. From agricultural machines to smart city cleaning robots or autonomously controlled drones, communication, especially with other agents operating in the vicinity, is critical. The ability of 6G to support subnetworks, having their dedicated resources, and being able to operate without infrastructure like BSs is deciding if those machines and robots can perform their actions reliably.

Cost-effectiveness

Cost-effectiveness is essential in developing semiconductor technologies, transceiver concepts, and digital/analog RF devices for energy-efficient and flexible applications and achieving cost efficiency, particularly in UE building blocks.

Multi-RAT diversity

Multi-RAT diversity combines at least two diverse access technologies to improve communication reliability. The effects, causing reliability enhancements, depend on the combination of technologies and redundancy schemes applied. Multi-RAT diversity enhances transmission reliability by increasing robustness against channel congestion.

Mobility/mobile network nodes

For some use cases, like connected cars, subnetworks, and public vehicles, 6G infrastructure is needed to provide connectivity for travelers and reliable automated driving applications.

Self-localization

For different use cases, specifically mobile radars, fusing mobile, distributed radar sensors requires many requirements, such as superior network architecture, real-time data processing, localization, and ultra-reliable low-latency communications. Moreover, many other use cases also need self-localization for efficient mobility management and planning.

Active network selection

Active network selection means the active choice of the UE to access a certain network. This requirement mainly points to NTN and their combination with given TNs. The choice shall be made with respect to certain network properties (availability, capacity, service requirements, etc.)

Cloud computing

Cloud computing basically describes the provision of computing services (e.g., servers, storage, databases, networks, software as well as analytics and intelligence functions etc.) via the internet (i.e., the "cloud") to support rapid innovation, flexible resources and economies of scale. As a rule, you only pay for the cloud services that you actually use. This allows you to reduce your operating costs, operate your infrastructure more efficiently and scale according to demand.

Edge cloud computing (for AI/ML)

Edge cloud/fog computing differs from cloud computing in that the cloud/computing is physically closer to the resources or devices on which the data is generated and/or the services are required (edge of the network). Edge clouds therefore enable lower latency times and better real-time capability. In terms of AI/ML, edge cloud computing is particularly helpful when it comes to inference (training with collected data can often be easily performed in "normal" clouds).

Network Capabilities Category

Scalability

Scalability is the ability of a network to accommodate growth and manage increased demand.

Device density

Density is the number of devices which can be accommodated in a given area.

Capacity/Backhaul

Backhaul describes the connectivity between base stations and radio controllers in cellular systems over a variety of transport media like wired based connection (copper or fiber) or wireless per radio transmission.

Transmission Time [4]

Note: We decided not to use the term "latency" as it is not clearly defined and thus understood differently depending on a person's background. Please read the following definition before answering.

Note: Real-time is also a subjective term that depends on the specific application (e.g., in some applications it means >10 min). We decided to reflect the real-time requirement using the transmission time, e.g. by stating a required mean value and a small deviation (e.g., 10 ms +- 1 us).

Transmission time is the interval between the moment of delivery of the first user data bit, or byte, of a message to the source reference interface and the moment of delivery of the final user data byte of the same message to the target reference interface.

Update Time [4]

- The interval between two consecutive messages received, i.e., the interval, measured at the target reference interface, between the delivery of the final user data byte of a message from a specific source and the delivery of the final user data byte of the following message from the same source.
- Background: This is specifically relevant for periodic traffic, as some applications pose restrictions not on the absolute value of the transmission time, but on the determinism with which the messages arrive at the destination. This is specifically relevant for transferring industrial protocols like PROFINET and/or safety-related messages like in PROFIsafe.

Response Time [4]

Response time is the interval between the moment of delivery of the first user data bit, or byte, of a request message to the source reference interface, and the moment the final bit, or byte, of the response message is delivered to the same source reference interface.

Synchronization

- If the communication network is required to support a time synchronization, the required accuracy is the key property to be stated.
- Synchronization in a computer network aims at delivering a common clock reference to nodes in the network within specific accuracy and stability. It is a prerequisite to establish and maintain a connection to

avoid collision, interference and giving the ability to UEs to communicate either directly or through an infrastructure-dependent network.

3D Sensing

3D sensing is ability of localization/object detection/sensing of object properties in 3D space.

Location accuracy

For localization: Accuracy is the closeness of agreement between a test result and the true value. Precision is closeness of agreement between independent test results obtained under stipulated conditions (variance).

Unit: meter

For (binary) detection: Accuracy is the overall probability that the result is true, i.e., (TP+TN)/(P+N). Precision denotes the probability that a positive result is true, i.e., TP/(TP+FP). T means "true", P is "positive", F is "false", and N is "negative".

Resolution and Separability

Resolution is the minimum range/delay, velocity/Doppler, or angular difference between targets to have measurably different results.

Service Area

Area in which the probability that the position error bound (PEB) is lower than a given threshold when the UE is at random positions with a random orientation.

Sensing estimate update rate

Number of consecutive localization/object detection/sensing estimates per unit time.

Trustworthiness Category

Trustworthiness

In the context of 6G networks, trustworthiness between stakeholders refers to the reliability, transparency, and security of interactions among the various entities involved in the development, deployment, and operation of the network.

Social acceptance

Social acceptance is the result of a process where stakeholders and project leaders work together to find solutions to these barriers and objections. It is important to be aware that the stakeholders affected by a new product or process go way beyond the small or medium enterprise's customer base.

Fidelity

Fidelity is the quality of being faithful that the transmitted signal represents the original information.

Security-by-design

Security-by-design means the technology is built in a way such that it reasonably protects against malicious threats successfully.

Availability

The availability of a network is the ability to perform the required functions or processes at any given time. How often a network fails and how long it takes to be healed or reconfigured are some of the factors that affect its availability. It refers to the probability of the system functioning at a given time and it is measured as a percentage.

Message loss

Message loss occurs when one or more packets transmitted across the network drops before reaching its destination causing an error to be produced in the data depending on the type of data transmitted (e.g., jitter in video conferencing, frequent gaps in audio communication, or broken-up images). It might be caused due to poor signal strength at the destination due to natural or human-made interference. For certain networks or systems, message loss can be measured by the percentage of dropped messages. It is important to have ultra-reliable communication systems with a low percentage of dropped messages, especially for mission-critical machine-type communications, such as industrial automation or automatic guided vehicles.

Resilience

Resilience is the ability of the network to provide and maintain an acceptable level of service in the face of various faults and challenges against the normal operation. It is highly influenced by the system design and its ability to tolerate the challenges that prevent the desired service delivery. Measurement of a system resilience is a collective of various parameters that shape the system's resiliency, such as QoS parameters: latency and throughput, dependability, and security, among others.

Non-public networks

A NPN is a network intended for non-public use. There are standalone Non-Public Networks (SNPNs) and public network integrated NPNs (PNI-NPNs). While SNPNs do not rely on any network functions from a MNO and are thus isolated, PNI-NPNs may be deployed as private slices with the support of a public land mobile network (PLMN) or involve another kind of support of a PLMN. The term NPN also includes the concept of private network [19].

Zero-trust

Zero trust is a security model that requires strict identity verification for every person and device trying to access resources on a private network, regardless of whether they are sitting within or outside of the network perimeter [20].

Regulation Category

Licensing

Licensing in the context of 6G refers to the process by which governments or regulatory bodies grant permissions to use specific portions of the RF spectrum for deploying their 6G networks. The RF spectrum is a limited resource, and its use needs to be managed to avoid interference and ensure efficient utilization.

Interoperability

Interoperability is the ability to communicate with pier systems and access the functionality of the peer systems. Establishing interoperability means to relate two systems together and remove any incompatibilities in between.

Flexible regulation

Flexible regulation refers to the efficient and flexible management of frequencies for telecommunications networks and services. The allocation and use of frequencies is based on flexible, objective, transparent, pro-competitive, non-discriminatory and appropriate criteria. The aim is to promote the harmonization of spectrum use for telecommunications networks and services to ensure their efficient and interference-free use and to achieve benefits for consumers, such as competition, economies of scale and interoperability of services and networks.

Features not matching the criteria to significantly benefit a use case family

[Flexibility] Flexible beam (de-)activation

Beam (de-)activation describes the process of switching the transmitting beam on and off. This feature mainly points at reducing the power consumption and therefore increases energy-efficiency.

[Flexibility] Highly dynamic beamforming

The term “beamforming” derives from the fact that early spatial filters were designed to form pencil beams in order to receive a signal radiating from a specific location and attenuate signals from other locations. “Forming beams” seems to indicate radiation of energy; however, beamforming is applicable to either radiation or reception of energy. Beamforming, in contrast to beam steering, is realized by altering the hardware, i.e., aligning them in a way, that by interference, a certain direction of the beam is preferred. In literature, there is a smooth transition between “beam forming” and “beam steering”.

[Flexibility] Flexible beam steering

Beam steering means “changing the direction of the main lobe of a radiation pattern. Note: In radio systems, beam steering may be accomplished by switching antenna elements or by changing the relative phases of the RF signals driving the elements. In optical systems, beam steering may be accomplished by changing the refractive index of the medium through which the beam is transmitted or by the use of mirrors or lenses. Beam steering, in contrast to beamforming, is mainly realized by changing the phase of the signal for each antenna in the grid to prefer certain directions. In literature, there is a smooth transition between "beamforming" and "beam steering".

[Flexibility] Scalability of independent streams and beams

The design of an advanced communication system requires multi-antenna capabilities with beamforming, scalable antenna sub-arrays, and mm-wave transceivers supporting large bandwidths. Efficient algorithms, compact assembly concepts, and RF semiconductor technologies are essential for handling data, addressing size challenges, and ensuring energy efficiency.

[Capacity] Bit rate per square kilometer

Bitrate per square kilometer denotes the necessary number of bits that are processed per unit of time to fulfill the demands of all UEs in an area of the size of 1 km^2.

[Capacity] Spectral efficiency

Spectral efficiency is measured in bits per second per hertz (b/s/Hz). With this value, one can easily calculate the amount of data bandwidth available in a given amount of spectrum. The spectral efficiency value, however, has multiple challenges. The value can refer to either peak spectral efficiency or average spectral efficiency. Average and peak spectral efficiencies differ because many of today’s wireless technologies adapt to the radio environment. Peak spectral efficiency is determined by the highest throughput a technology can deliver in a given amount of spectrum, occurring with the highest order modulation scheme available and the least amount of coding.

[Capacity] Physical layer bit rate

Physical Layer Data/Bit Rate: defines the transmitting of a stream of raw bits over a physical data link. Bit stream may be grouped into code words or symbols and converted to a physical signal that is transmitted over a transmission medium.

[Sustainability/Energy Efficiency] Energy efficient transmit power for NTN

Effective radiated power (EIRP): In a given direction, the relative gain of a transmitting antenna with respect to the maximum directivity of a half-wave dipole multiplied by the net power accepted by the antenna from the connected transmitter.

[Sustainability/Energy Efficiency] Energy per unit of traffic

Energy per Unit of traffic: Used energy of the communication system per Information content. Similar measuring units: energy per connection (Wh/connection), energy per cell site (Wh/cell site), energy per revenue (Wh/Euro).

[Sustainability/Energy Efficiency] Transceiver and multi-antenna systems efficiency

Transceiver and multi antenna systems efficiency is the energy efficiency of the transmit and receive chain of the communication system, which can be measured by the energy per unit of traffic.

[Privacy] Unlinkability

Unlinkability of two or more items (e.g., subjects, messages, events, actions, etc.) means that an attacker cannot know better about the relations of items within a system after observing or influencing the system. Regarding communications this means that messages cannot be linked to senders or receivers or to link subscription concealed identifiers (SUCI)s.