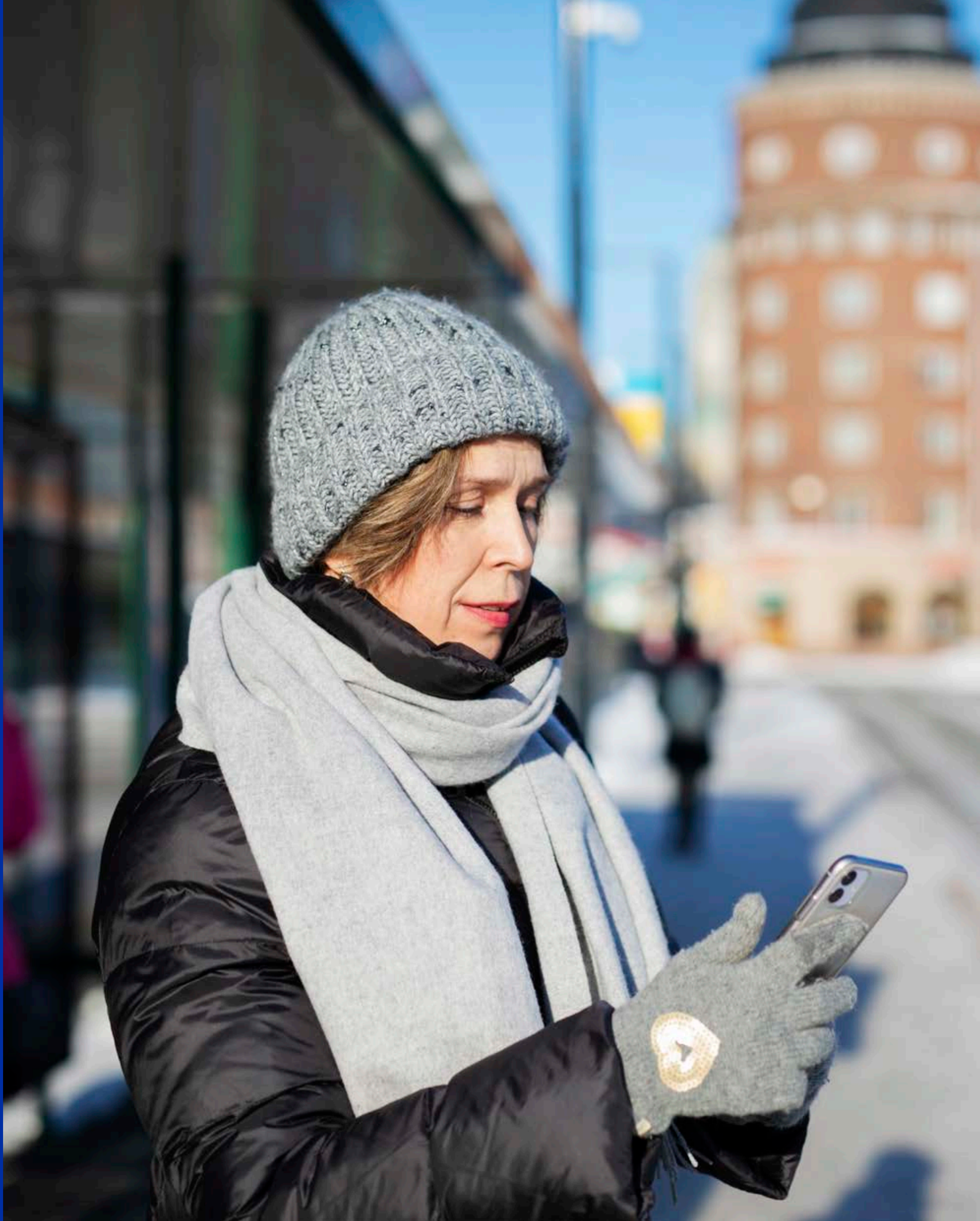
BUSINESS
FINLAND

B5G AND 6G

National Strategic Research and
Innovation Agenda (SRIA)



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GLOSSARY

3GPP	3rd Generation Partnership Project (mobile network standardization)
5G PPP	5G Public Private Partnership (European Commission 5G research partnership program)
5G	5th Generation Mobile Network
5G-A	5G-Advanced
5GTNF	5G Test Network Finland
6G	6th Generation Mobile Network
AI	Artificial Intelligence
API	Application Protocol Interface
AR	Augmented Reality
B5G	Beyond 5G
CA	Carrier Aggregation
Cobot	Collaborative Robot
CU	Centralized Unit (RAN component in mobile network architecture)
DC	Dual Connectivity
DSP	Digital Signal Processing
DU	Distributed Unit (RAN component in mobile network architecture)
E2E	End-to-End
ETP	European Technology Platform
ETSI	European Telecommunications Standards Institute
EU	European Union
GDP	Gross Domestic Product
GSM	Global System for Mobile Communications
GSM-R	GSM-Railway
HAPS	High Altitude Platform
HW	Hardware
IAB	Integrated Access and Backhaul
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IPR	Intellectual Property Rights
ISAC	Integrated Sensing and Communications
JU	Joint Undertaking
KPI	Key Performance Indicator
KVI	Key Value Indicator
LEO	Low Earth Orbit
LTE	Long Term Evolution (4th generation mobile network long term evolution)
MDT	Minimization of Drive Testing
MEC	Multi-acess Edge Computing
MIMO	Multiple-Input/Multiple-Output
ML	Machine Learning
mmWave	Millimetre Wave
MNO	Mobile Network Operator
MR	Mixed Reality
MTC	Machine Type Communication
MU-MIMO	Multiuser MIMO
NFR	Non-Functional Requirement
NPN	Non-Public Network
NSA	Non-Stand Alone
NTN	Non-Terrestrial Network
ONF	Open Network Foundation
O-RAN	Open Radio Access Network Alliance
PHY	Physical Layer
PoC	Proof-of-Concept
R&D&I	Research and Development and Innovation
R&D	Research and Development
RAN	Radio Access Network
RedCap	Reduced Capacity Basestation
RU	Radio Unit (RAN component in mobile network architecture)
SA	Stand Alone
SBA	Service-Based Architecture (3GPP)
SDG	Sustainablity Development Goal
SD-RAN	Software-Defined Radio Access Network platform
SNS	Smart Networks and Services
SON	Self-Organizing Network
SRIA	Strategic Research and Innovation Agenda
SW	Software
TDD	Time Division Duplex/Duplexing
TEF	Testing and Experimentation Facilities
THz	Terahertz
TN	Terrestrial Network
TRP	Transmission Point
TSN	Time Sensitive Networking
UAV	Unmanned Aerial Vehicles
UN	United Nations
URLLC	Ultra Reliable Low Latency Communications
V2X	Vehicle to everything communication
VR	Virtual Reality
vRAN	Virtualized RAN
WRC	World Radiocommunication Conference
XR	Extended Reality

TOWARDS 6G – FOREWORDS

Finland has been a forerunner and leading the mobile communications development during the past decades since the GSM was launched. Telecommunications is also one of the key technology and industry areas from which Finland is globally known of, and that has been pushing all our digital development ahead. In the new digital era, this work is more and more important as the work directly contributes to the development of other industries and the digital infrastructure of our society.

In Finland, Tekes and Business Finland have invested in the telecommunications area for more than two decades and funding programmes such as Ubicom, Giga, Trial and 5thGear were established to support the collaborative R&D&I work. In addition to the numerous telecommunication research projects, this work has facilitated many contributions to standardization through, e.g., 3GPP (for telecommunications standards) and WRCs (global world radiocommunication conferences by ITU for radio frequencies regulations), and several large-scale collaboration projects have taken place on the European level in different Framework Programmes, the latest ones being Horizon 2020 and Horizon Europe.

The work towards 6G – both nationally and internationally – started in 2018 through 6G Flagship, the flagship project funded by the Academy of Finland. As a pioneer, it has been supporting the R&D for B5G (Beyond 5G) and early research for 6G. Moreover, Finland has been leading the Hexa-X EU projects for the European 6G vision creation and early industry involvement. At the same time, competition is getting more and more fierce. Other countries and actors are challenging our leading position, so we need determined actions to ensure our competitiveness in the global landscape.

With this in mind, Business Finland has decided to launch a new funding programme 6G Bridge that paves the way for 6G and aims to help in maintaining the Finnish forerunner status. During the 5G collaboration era in Finland, to complement the traditional approaches and ways of working, the Finnish test networks were connected under the 5G Test Network Finland (5GTNF) brand and innovation collaboration work was done more and more in the context of industry verticals including smart cities, smart energy, smart ports and smart factories with different ecosystem players. These provide a concrete and versatile foundation also for the new 6G collaboration – both from the mindset and impact points of view.

This Strategic Research and Innovation Agenda (SRIA) provides an excellent referential roadmap for the 6G Bridge programme. In addition, it is concrete evidence of the unique industry-academia and ecosystem cooperation that we have in Finland, and that is one of our assets in the global competition.

In Shanghai, China 14.9.2022.

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EXECUTIVE SUMMARY

In this strategic research and innovation agenda, we present the Finnish research community's view on research and development towards future 6G mobile and telecommunication system. We outline strategic objectives, implementation challenges, and roadmaps over the next decade, covering 5G, 5G-Advanced, and 6G technologies. The work has been carried out during spring and summer 2022, in parallel with European research and innovation agenda preparations. Although, the 5G and 6G research and development is a global effort, this document has been built to reflect the key research, development, and innovation goals of the Finnish industry, academia, and stakeholder groups.

The vision for 5G evolution and 6G is formed around three main pillars; **performance, sustainability** and **security/trustworthiness.** First, the future mobile telecommunication system's performance needs to be quantitatively better than the current one. This implies that the target key performance indicators, such as peak data rates, latency, jitter, spectral efficiency, device density, etc., should be far better than the current 4G and 5G basic systems can provide. Majority of the work in boosting the mobile network system is and has been concentrating on the radio link, radio access network, and packet core gateway functions. However, the overall end-to-end system performance can be guaranteed only when ensuring and updating all the functions, protocols, and components of the system to fulfill the requirements of applications and services, starting from digital and analog radio and antenna components, up to hardware and software platforms and functions at access stratum and finally to packet routing and transport/application protocols over the packet switched network and Internet. The flexibility and scalability of the system can also be counted as the performance boosters. Flexibility means that the system should be easily optimized and managed, but also easily tailored for various use cases. Scalability implies system capabilities to scale from local and private network systems to global systems in a sustainable way. This requires modular performance improvements from the same base system and, e.g. use of non-terrestrial networking such as satellites. Therefore, the software design and software tools, including the methods for developing, managing, and arranging virtualized micro or nano functions, massively distributed heterogeneous software systems, and the evolution of telecommunication system Service-Based Architecture (SBA), are important research and development topic. For flexibility, the automation of system management and utilization of machine learning and other expert system solutions for zero-touch resource and service orchestration and provisioning are essential.

While increased performance is an important goal, sustainability and security are the key system features. For sustainability, the United Nation's Sustainability Goals are also driving the future mobile network development. Thus, the following viewpoints should be taken into account in the overall system:

1. The system needs to be stable, reliable, agile, and sustainable not only from energy consumption point of view but also from lifecycle of system core components, and operations point of view. Telecommunication system sustainability needs to be verified also from economical and social viewpoints.

2. The system needs to be secure and resilient, and provide a platform which is natively trustworthy from users and the system operators/service providers point, and enable tailored security as a service for different operations and use cases.

3. The system needs to be easily manageable, which requires a level of automation in network and system management but having human in the loop. The efficient end-to-end management of resources leads to complex system optimization problems where system global optimum cannot be found using local optimization.

In addition to the technical focus areas of 5G, 5G-Advanced and 6G, we present the roadmap for testbed and experimentation platforms required to supporting the research and enabling the validation and verification of the different Key Performance Indicators (KPIs) and Key Value Indicators (KVIs) related to the mobile networks and use cases. One important aspect would be to enable end-to-end system KPI and KVI validations, as for now there are not yet holistic 6G system validation platforms, design and creating such would be important. In addition to simulations, emulations or twinning of the 6G holistic platform, we should perform 5G and 5G-Advanced validation, demonstration tests, and trialling with real world use case scenarios.

The document provides insights for foreseen impact of the technology research and development to the society, industry, and research community. As a summary we see that opportunities provided by 5G and 5G-Advanced will provide more imminent impact to the society and industry through cross-sectoral innovations and IPR. The impact to society comes also from the various application and use cases related, e.g., to safety, security of supply and communal services provided with mobile technologies. For 6G, the impact to research and telecommunication industry is perhaps more imminent, as the main 6G applications are still to be developed. Boosting the IPR development in telecommunications, creating new workplaces and attracting new talents to Finland are ones to mention, which also impacts to the society.

Finally, the vision of future telecommunication R&D&I in Finland is well aligned and scheduled with global activities, emphasising the Finnish national goals. In alignment, especially with the European Union activities in Smart Networks and Services Joint Undertaking (SNS JU) and collaboration with NetworldEurope European Technology Platform (ETP) and 6G Industry Association (6GIA) are of importance.

1. INTRODUCTION

Globally the 6G research is starting in earnest, although in Finland the academic research has already been ongoing for a few years giving some advantage to Finnish players. The first coming years will be spent on research to develop enabling technologies to make expected new applications and services possible. Different use cases are studied to find a basis for coming standardization. The foreseen 6G has several challenges to be tackled to obtain technology, societal, and business requirements set by the different use cases. From a technological point of view, it is important to ensure a smooth transition from 5G and 5G-Advanced (5G-A) to 6G without sacrificing too much technical capabilities for maintaining constant evolution. In order to maintain Finland's good position in the mobile networking business, new experts need to be trained and IPR developed. This entails the need to have large and long-lasting research and development projects and of course funding for them.

In this research and innovation agenda, we introduce the main strategic objectives, implementation challenges, and roadmaps for future development of 5G, 5G-Advanced, and 6G technologies. In addition, we summarize the need of experimentation and test environment from Finnish R&D perspective.

The second chapter provides insight for the development needs and targets of the current state-of-the-art 5G technologies. As 5G is approaching its end on the 3GPP standardization path and the standardization is stepping towards 5G-Advanced technologies, one of the main targets for 5G R&D will be enhancements and development of already standardized 5G functionalities, system components, and interfaces for vertical use cases. There is still a plethora of key strategic objectives for 5G development in the near future, starting from sustainability, security, and privacy to efficient use of software, artificial intelligence (AI), and machine learning (ML) as well as optimization and efficient resource use of the network for new services. Advances, especially to enable larger societal impact, have been seen as key objectives and national priorities.

The 5G-Advanced, discussed in Chapter 3, shares similar implementation challenges as 5G and the main application areas and use cases are built on top of the 5G use cases. There are, however, some additional requirements and enhancements to be considered. For example, the extended reality applications will be more in focus from system performance optimization point of view. Advances in non-terrestrial networks (NTN) are seen important for Finnish stakeholders. Long-term 3GPP standardization activities focus mainly on AI/ML use in the air interface and extreme radio performance. The use cases consider, for example, 5G for railways, car-to-car communications, public safety and unmanned aerial vehicles (UAVs), as well as joint sensing and communication enablers.

In Chapter 4, we present the roadmap and objectives for the 6G research and development. Although the generic challenges and key technology areas follow the previous generations, there are several foreseen advances, starting from new radio technologies to holistic system optimization and new services and devices. 6G architecture will become three-dimensional, covering airborne and satellite platforms. It can be said that the most important challenge for 6G will be sustainability and trustworthiness. Sustainability, not only considering the energy efficiency, but also lifecycle of the system core components, hardware and software, and operations point of view. Trustworthy, as being also secure, reliable, stable, and resilient, providing the environment and platform which can be easily tailored and arranged for use variety of vertical use cases with sufficient performance characteristics.

Chapter 5 provides the insight to required test and experimentation environments to conduct and validate the R&D work for novel mobile network technologies. In this Chapter we also present roadmap for 5G, 5G-Advanced and 6G trials and piloting, together with required testbed enablers and foreseen proof-of-concept development of key use cases.

2. 5G

2.1 STATE OF THE ART AND FUTURE OUTLOOK

Finland was one of the forerunners in 5G mobile network system development. Tekes 5thGear Program (2014-2019) started in align with the global 5th Generation Mobile Network standardization and definition activities. The 3GPP standardization work started officially in 2015 and the specification was released in 2017. At the same time with the 5thGear Program also the European Commission started a new public private partnership for 5G development, i.e., 5G PPP within Horizon2020 framework program. During the 5thGear Program, the main definition of the 5G system functionalities, system architecture, new air interface and waveform, as well as spectrum allocations for the 5G basic system were defined. The main Finnish stakeholders were highly involved in these activities.

Today we have been closing the standardization activities of the 5G system and its evolution, looking forward to the next step, i.e., the 5G Advanced system. It will be defined during the next 3GPP standard releases to support the enhanced capabilities of 5G for the different vertical industry needs and performance-critical applications, as well as research and development of the next generation 6G.

The disaggregation of the radio access network and software-based architecture approaches for the 5G system are continuing in 5G-Advanced standardization, and for example through Open RAN (Radio Access Network) and Virtual RAN approaches within various activities in, e.g., 3GPP, O-RAN Alliance and Open Network Foundation (ONF).

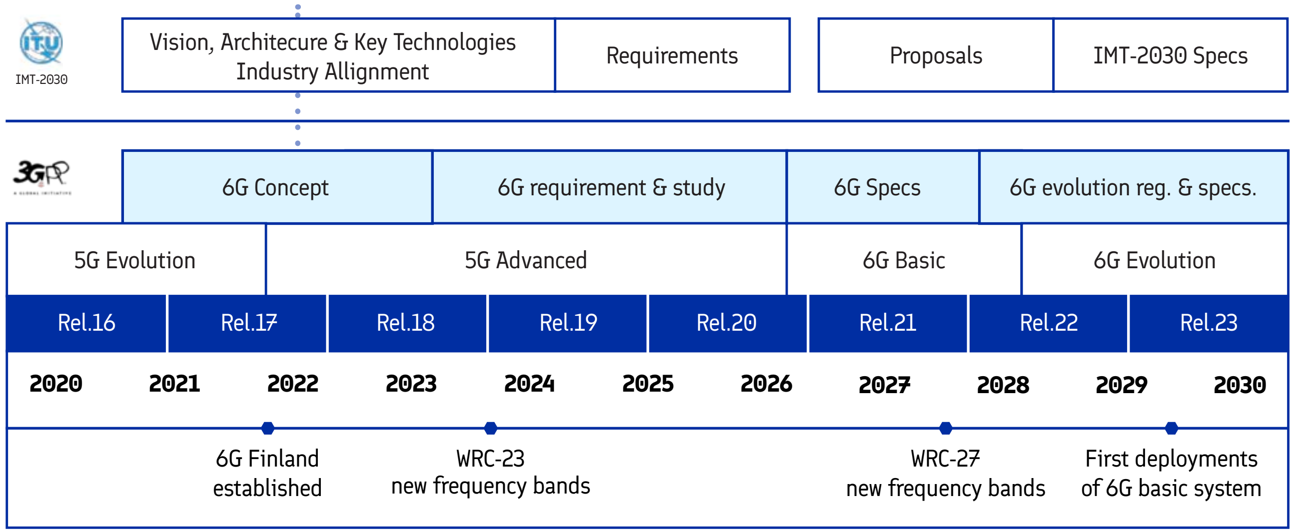


Figure 1. Roadmap and Schedule for ITU and 3GPP towards 6G

In the Open RAN concept, the disaggregation is divided into three main building blocks: Radio Unit (RU), Distributed Unit (DU) and Centralized Unit (CU). The key idea is to open the protocols and interfaces with the building blocks and provide enhanced capabilities to monitor and control the resources of the RAN. The key advantage of Open RAN is that it enables the expansion of ecosystem with more vendors capable of providing different building blocks, software and AI components for radio network management, and optimization and software components for the DU/CU environment. The AI components can be introduced via so called RAN intelligent controller, which may function either in near-real-time or non-real-time mode in the control plane. Cloud RAN / virtualized RAN (CloudRAN / vRAN) is another concept, which targets to implement the RAN functionalities as virtualized network functions, i.e., as software components on top of the software virtualization platform. This enables more flexible architecture and orchestration of functions even in a hardware independent way. The virtualized RAN which utilizes open interfaces and protocols can be called also Open RAN. Examples of Open RAN initiatives and alliances providing the architecture specifications are O-RAN and Open Networking Foundation's (ONF) SD-RAN.

Although these Open and cloud / virtualized RAN concepts provide changes to the 5G RAN architecture, they can be seen as extensions of 5G as providing the enhanced capabilities to control and manage the resources of the radio access network using specific 5G waveforms, radio and antenna solutions, core network functionalities and 3GPP specified protocols for 5G.

The standardization and regulations of the 5G system are moving towards the 5G-Advanced. However, the development of 5G technologies is still needed, especially for optimizing 5G for the vertical industry needs, private network extensions and interoperability between private and public networks. The focus on 5G R&D is the applicability of 5G for industry and society needs, boosting the deployment and services provided for end-users and end-customers. Activities should be linked also to trials and experimentations, e.g., through the test and experimentation network facilities.

2.1 STRATEGIC OBJECTIVES

The key strategic objectives for 5G development will include:

1. **Sustainable 5G;** sustainability includes energy and spectrum efficiency, intelligent resource optimization and extending the lifecycle of products and services. Sustainability also includes methods to guarantee the quality of the highly distributed software systems and their long-term maintenance. What are the measurements and criteria of sustainability, and the impact to vertical industry and end-user applications. Development of multi-access and multi-path optimization and energy efficient broadcast and multicast communication are foreseen.

2. **Security, privacy and trustworthiness;** enabling end-to-end secure communication and trustworthiness of communication, secure service and software platforms, dependability of 5G system and edge-cloud computing continuum for critical services and applications.

3. **Usability of Machine Learning and Artificial Intelligence in 5G, and 5G for edge AI;** ML and AI strategies and solutions to enable end-to-end optimization, enabling AI in edge-cloud continuum, distributed and federated learning methods for 5G system and its applications, edge AI with 5G connectivity.

4. **Automation of networks and troubleshooting;** including the self-management and self-organization, self-orchestration of management functionalities, end-to-end network automation and resource optimization.

5. **Private and enterprise networks, industrial innovation;** 5G technologies for vertical industries to enable greater societal impacts through smart cities, public safety, authority networks, healthcare, manufacturing, industrial automation etc. Cellular IoT and mesh network for verticals. Enhancing 5G end-to-end platform for mission critical applications.

6. **Usability of mmWave frequencies;** new frequency bands for terrestrial and non-terrestrial network integration for vertical application domains, efficient use of 5G spectrum, spectrum sharing and aggregation, utilizing current 5G solutions and networks as a sensor.

7. **Network optimization for new 5G services;** extended reality applications and other performance critical services and applications, haptic remote control, services for automatic driving, enabling time sensitive and deterministic networking etc.

8. **Positioning beyond indoor and satellite-based positioning;** hybrid technologies with extended positioning accuracy in challenging radio environments, utilizing AI for improving the accuracy, securing the system from spoofing and jamming.

9. **Communication system product modelling and functional simulation integrated to virtualized environment (digital twin);** enabling the modelling hardware and software components and their interoperability in virtualized environment.

10. **Ecosystems of Highly Distributed Applications and Software;** enabling automatic scaling and orchestration of the software for vertical applications. 5G and 6G will bring an exponential growth of the network devices and their software, and therefore novel orchestration and scaling approaches for the vertical applications will be needed.

11. **Enterprise-Level management of 5G and 6G software architectures;** management of edge and IoT devices and their software. Developing and managing 5G and especially 6G software will demand novel software development methods, tools, processes and architectures. The number of connected devices is expected to explode, and they all have software. They range from micro-level devices with very limited processing capability to larger connected devices with strong processing power and up to large applications in the cloud. The software development for these complex, heterogeneous and highly distributed systems require novel architectures, methods and tools.

The main objectives include the improvement of the 5G system to support and enable better uplink capacity as it is one of the major enablers for, e.g., industrial applications. The overall objective is to improve sustainability and security / trustworthiness of the end-to-end communication system. As the currently standardized 5G basic system is still lacking of system enablers for sustainability and trustworthiness in different application areas, these are the main development targets also for upcoming mobile network standard releases of 5G-Advanced and 6G.

2.3 IMPLEMENTATION CHALLENGES

One of the major challenges for 5G deployment, and taking all the standard specified features into practice, is to enable and justify the business opportunities for those functionalities. All the functionalities and features to be implemented need to be commercially viable, i.e., there is not only a technological motivation to implement and deploy the new features, but there needs to be demand and business for it. Thus, it is important to show and trial new features of 5G for different stakeholders and stakeholder groups.

The current 5G deployment is targeting mainly for extending the broadband capabilities of widespread LTE networks in dense urban areas for mobile network users. Many already specified functionalities and capabilities for critical use cases, time critical and sensitive applications, remote areas etc., are not deployed, tested and implemented. The R&D work for enabling the system features are still needed as well as the large-scale validation and experimentation of the features and especially the optimization of the whole end-to-end communication system.

Some of the challenges lie in cost, both in operational as well as capital expenses of the system. Minimizing both the manufacturing costs as well as purchase and operating costs are key challenges. The solutions may come from softwarization/cloudification and enablement of AI/ML in operations and management. Thus R&D work for 5G should continue especially on usability of AI/ML for network and resource management.

The minimization of costs impacts sustainability, for example through lifecycle extension of hardware and software components. One of the challenges is thus, how the different system components can be efficiently used in the 5G to 5G-Advanced transition. From the sustainability point of view, it would be unbearable to expect the system hardware component change and redesign for every system release.

To enable the use of the 5G system in critical and challenging environments, one must validate and verify the system reliability and dependability for the applications. These environments and use cases include most of the industrial applications, critical systems, e.g., for security of supply (water, energy, logistics, tracking and monitoring goods and supply reserves etc.), public safety and defence.

The dependability issues will also arise for AI/ML based intelligent management of the system, for example, how to manage, control and trust the system and AI driven management, and keep still the human in the loop for critical system management and control. As the system will be more and more complex, understanding the complex system behaviour will be important to plan the optimization and management strategies, and to enable the efficient monitoring and control of the system. In addition, ability to plan and train the AI/ML methods, and arrange the problem mitigation solutions / troubleshooting will be key challenges to tackle.

2.4 APPLICATION AREAS AND USE CASES

The main application areas for 5G are still to provide coverage extension to current mobile networks as well as to improve the performance of broadband connectivity and applications for end-users. It is foreseen that the deployment will gradually extend from densely populated areas and big city centres towards the countryside population centres and main roadways. However, the full national geographical coverage is hard to see within the next few years. 5G could be dominant technology especially in private and local networks for industrial use, serving the needs for both broadband and massive IoT with sub-6GHz and millimetre wave frequencies. This would however imply the full transition to standalone (SA) 5G radio solutions. As mentioned in the challenges, the capabilities of 5G should be demonstrated well for vertical industries with viable business opportunities.

Some of the main application areas and use cases were already mentioned in the previous sections. It would be important to focus on large societal impact including the use cases and application areas for smart cities, public safety and security, security of supply, extending the authority networks and services beyond the 4G and e.g., Virve 2.0, streaming applications, aerial platforms, as well as enabling reliable and optimized/tailored connectivity for industrial needs in challenging environments. These industrial areas include ports, mines, factories, manufacturing plans, energy supply infrastructures and water supply.

2.5 EXPECTED IMPACTS

2.5.1 SOCIETY

5G technology enables unforeseen levels of connectivity, upgrading 4G networks with enhanced functional drivers: superfast broadband, ultra-reliable low latency communications, massive machine-type communications, high availability and efficient energy usage. These drivers intensify productivity and economic development while creating new jobs and supporting environmental efficiency initiatives launched by businesses and communities.

5G is more open than the previous mobile network generations boosting opportunities for cross-sectoral innovations. It supports collection of data from a myriad of Internet of Things (IoT) devices, efficient AI/ML based data processing, and decision making at the network edge. These together enable creation of new smart services (for example in the field of smart cities, smart buildings and smart traffic) for the citizens and authorities.

2.5.2 INDUSTRY

5G with its advanced capabilities (higher bit rates, lower latencies, ultra-reliable communications) opens the door for industry 4.0 and enables digital transformation in the industry. 5G networks offer manufacturers and telecom operators the chance to build smart factories and take advantage of technologies such as automation, artificial intelligence, and augmented reality. 5G offers digital connectivity, not only for the people, but also for sensors, machines and IoT devices.

Advanced features of 5G make is possible to have wireless “critical communications” in real time. This benefits applications such as mobile robots in production, autonomous vehicles in the transportation and logistics sectors, Industrial IoT, augmented reality applications for service and maintenance technicians, and virtual reality applications for users. Edge computing and AI/ML along with reliable communications are the key factors to have intelligent decision making and fast response times that enable industry 4.0 to take place.

2.5.2 RESEARCH AND ACADEMIA

5G research educates a new generation of mobile network experts while developing new wireless network technology and abilities to apply 5G technology in vertical applications. 5G applied to different use cases increases multidisciplinary research and spreads understanding of the 5G. It will be easier for researchers working on verticals to see how 5G can be applied in their own fields. On the other hand, 5G researchers get more understanding of the verticals and requirements set by them to wireless technologies. 5G technology as such opens new possibilities to arrange education and enable students not only learn how to use advanced technologies, but also how to develop and create with them.

2.6 ROADMAP

The standardization of 5G within 3GPP is currently moving towards 5G-Advanced as depicted in the Figure 1. The work for 5G is now turning more towards vertical application domains of 5G and further development of standardized functionalities for both radio and network to fulfill the vertical application and use case needs.

The Figure 2 summarizes the main segments, foci of the segments and related functionalities specified per standard release. The segments include, Industrial IoT covering ultra-reliable and local connectivity, radio boosters providing enhanced performance especially for mobile broadband connectivity, new verticals with focus on non-terrestrial networks and public safety, and automation of deployment introducing, e.g., integrated access and backhaul as well as enablers for self-organizing network.

Considering the main European communication network research and innovation agenda, the focus is on 5G evolution and initial 6G research. The main 5G research was carried out during the Horizon 2020 Framework Programme, especially within the 5G PPP partnership program. However, there is still a lack of large-scale experimentation and testing facilities to boost the deployment and validation of 5G in different vertical use cases.

SEGMENT	FOCUS	RELEASE 16	RELEASE 17
Industrial IoT	Ultra-reliable & local connectivity	URLLC/TSN Unlicensed band Private networks (NPN) Positioning	TSC 60-71 GHz RedCap (NR-Light) Accurate positioning
Radio boosters	Extreme radio performance	Enhanced MIMO UE power saving Mobility enhancements DC/CA improvements	Further enhanced MIMO Further power saving Multi-TRP uplink DC/CA enhancements Coverage enhancements
New Verticals	Use cases	V2X	NTN/HAPS Public safety; sidelink & multicast
Deployment automation	5G fast rollout	IAB SON/MDT	IAB enhancements SON/MDT enhanced

URLLC = Ultra Reliable Low Latency Communication
TSN = Time Sensitive Network
NPN = Non-public Network
TSC = Time Sensitive Communications
MIMO = Multiple-Input / Multiple-Output
DC = Dual Connectivity
CA = Carrier Aggregation
TRP = Transmission Point
V2X = Vehicle-to-X
NTN = Non-Terrestrial Network
HAPS = High Altitude Platform
IAB = Integrated Access and Backhaul
SON = Self-Organizing Network
MDT = Minimization of Drive

Figure 2. 3GPP 5G Radio standardization releases 16 and 17.

The experimentation platforms are important especially for the development of smart cities and city services. There are challenges in arranging such environments and in most cases, it is not only due to technical challenges, but more of e.g., regulatory or financial challenges. These hinder the development and deployment of large-scale experimentation and testing environments[1], and thus, not directly related to 5G development. However, the European smart city network, EUROCITIES, have published also requirements for 5G. These requirements include responsible and fair deployment of 5G including minimizing the impact of 5G to environment and human health, and preservation of visual identity of public spaces in deployment[2]. The latter impacts the design, packetization and implementation of, e.g., antennas and radios in cultural and preserved environments or other public spaces.

[1] https://futurium.ec.europa.eu/sites/default/files/2021-03/Final%20-%20Action%2011%20and%2012%20external%20review%20-%20VTT.pdf
[2] https://eurocities.eu/wp-content/uploads/2020/08/EUROCITIES_statement_on_5G_.pdf

3 5G ADVANCED

3.1 STATE OF THE ART AND FUTURE OUTLOOK

In 3GPP standardization, the work on the first Release of 5G-Advanced has just started in mid-2022 and Release 18 is expected to be completed in March 2024, with some elements later during 2024. The first field deployments of 5G-Advanced are then expected in the 2025 timeframe. As part of the 5G-Advanced work, some topics are done as preparatory studies for the next Release, Release 19, which would aim to be completed by end of 2025 or early 2026, with field deployment around 2027. Thus 5G-Advanced will be bridging 5G and 6G, before any 6G specifications would get completed in 2028 or 2029 in 3GPP. Parallel to 3GPP 6G studies further work in 5G-Advanced would be covered then in Release 20.

Many of the topics, which are foreseen for 3GPP Release 19, and which are based on the study topics already for Release 18, are such that will be part of the 6G foundation. These topics are also currently discussed a lot in academic research for the 6G system. These topics include, e.g., combined sensing and communication, use of machine learning / artificial intelligence in the air interface as well as in RAN and core, further power saving technologies for sustainability, edge computing with XR, passive IoT, and full-duplex considerations.

On topics, such as sensing, the use cases raised cover solutions such as air quality monitoring or smart city use cases like traffic control. With machine learning, the research challenges include how to utilize machine learning with limited resources in network and user equipment, and how to achieve solutions which allow verification of performance and filling the regulatory requirements in all scenarios.

The development of 5G-Advanced will offer still plenty of room for new ideas and innovations until 6G specifications will be ready in 2028/2029. Many topic areas and specific functionalities developed for 5G-Advanced are foreseen to define the directions of 6G development, as many of basic 6G features will be built directly on top of solutions defined in 5G-Advanced in 3GPP Releases 18, 19 and 20.

3.2 STRATEGIC OBJECTIVES

To tackle the generic 5G-Advanced challenges, the following technology areas need to be investigated:

1. **Multi-access Edge Computing with XR;** the 5G-Advanced is expected to provide multi-access edge computing that is deeply integrated with the network architecture enabling new more local application functions, such as XR-related interaction, rendering and real-time applications.
2. **AI in the RAN / Core Network / Air Interface;** 5G-Advanced is expected to feature in-network AI capabilities that will benefit both network management and orchestration as well as wide range of applications, but also targeting the use of AI/ML in the air interface to improve performance. This work will form the basis for AI/ML in 6G.
3. **RAN architecture disaggregation, and network management and orchestration;** the current trend of disaggregating the network based on well-defined open APIs, protocols, and functions is expected to continue. Network orchestration is a crucial component of 5G-Advanced and beyond for configuring and optimizing the programmable network to meet the application-specific requirements.
4. **Sustainability, including energy optimization and efficiency;** mobile network and application sustainability will be crucial for 5G-Advanced and beyond networks. This research topic covers a lot of ground from materials and energy use to the way the end-to-end data and applications work.
5. **Sensing and communication;** combined sensing and communication will be the basis for sensing in 6G, first foreseen to be developed on top of the 5G-Advanced capabilities with further extension in 6G. Expansion of 3GPP-based solutions to new domains, such as radio-based solutions enhanced with a fusion of sensors, visual localization and sensing. The key issues included with sensing start from the understanding of the use cases such as traffic monitoring/control, environmental monitoring (air quality, climate change, microclimates), and XR. The technical areas include full-duplex operation, achievable accuracy with 5G-Advanced limitations on different frequency bands, relationship to positioning, orientation, and impact on the end-user privacy. The development with sensing is foreseen to start from sensing assisted communication and moving towards sensing as a service for detecting different objects, using also possible other means than just 3GPP radio signals for sensing, such as cameras, radar and other sensors.

6. **Expanded positioning;** 5G-Advanced Rel-18/19 is approaching millimetre-level positioning accuracy for the generic positioning framework. Even if the positioning accuracy and latency would allow most of the use cases, the specific support for vertical applications requires enhancements for methods, protocols, interfaces and network architecture support.
7. **Highly Distributed Applications and Software;** enabling automatic scaling and orchestration of the software for vertical applications. 5G and 6G will bring an exponential growth of the network devices and their software, and therefore novel orchestration and scaling approaches for the vertical applications will be needed.
8. **Enterprise-Level management of 5G and 6G software architectures;** including management of edge and IoT devices and their software. Developing and managing 5G and especially 6G software will demand novel software development methods, tools, processes and architectures. The amount of connected devices is expected to explode and they all have software. They range from micro-level devices with very limited processing capability to larger connected devices with strong processing power and up to large applications in the cloud. The software development for these complex, heterogeneous and highly distributed systems requires novel architectures, methods and tools.

3.3 IMPLEMENTATION CHALLENGES

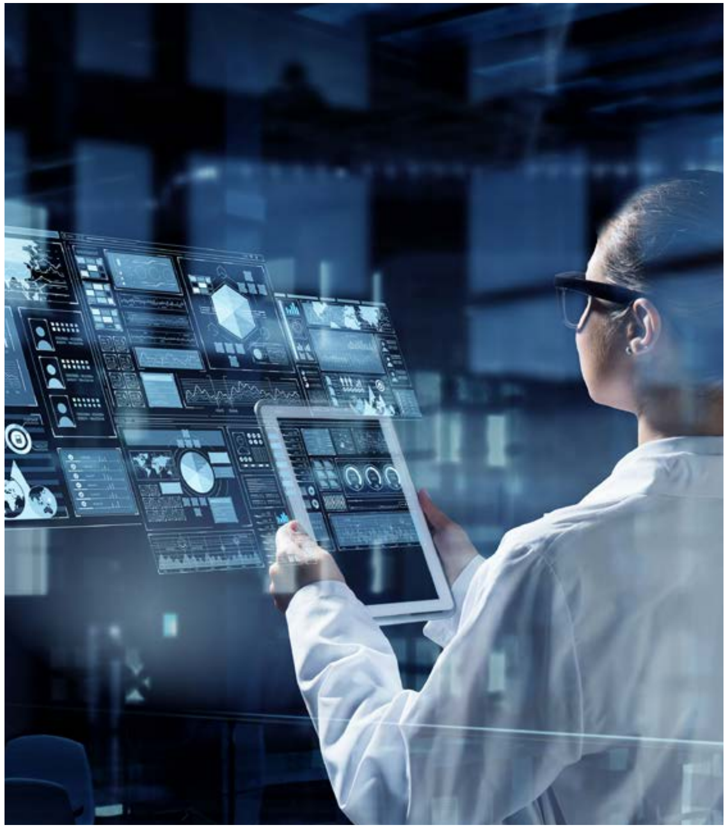
The 5G-Advanced implementation challenges are basically the same as with 5G (see chapter 2.3), but in addition one needs to consider the upcoming transition towards 6G. The main challenges, related also to the application of 5G-A technology for vertical industry, include how efficient and reliable the system will be. The uplink capacity and performance of radio are essential for a variety of industrial applications as well as critical infrastructures. In addition to performance and reliability, the solutions for enhanced security, sustainability and energy efficiency are required. These create the challenge to find balance between end-to-end system and network performance, energy-efficiency, and security and trustworthiness. As the visions of new end-user devices already for 5G-A era include the distributed user devices and multimodal user interactions, means how the network will support the highly distributed end-user terminal approach for different application scenarios such as XR or haptic remote control of machines should be considered. From system and end-to-end service security point of view, the challenge is not only on securing and hardening the communication links, application and protocol interfaces, and control and data plane data flows, but also to harden the edge and in-network processing and software platforms, virtualization and orchestration functions, as well as AI in edges and for system management and control automation. As the complexity of system management and control increases with new functionalities and varying requirements to tailor system for multiple different use cases, more automation is needed to make the network operation and management easy. Applying AI for management and optimization of system, requires also securing and hardening AI and ML for management, and additionally enabling energy-efficient and energy-aware use of AI and ML. To keep better humans in the loop, use of AI would require also applying explainable AI for telecommunication system optimization.control increases with new functionalities and varying requirements to tailor system for multiple different use cases, more automation is needed to make the network operation and management easy. Applying AI for management and optimization of system, requires also securing and hardening AI and ML for management, and additionally enabling energy-efficient and energy-aware use of AI and ML. To keep better humans in the loop, use of AI would require also applying explainable AI for telecommunication system optimization.

3.4 APPLICATION AREAS AND USE CASES

The 5G-Advanced application areas and use cases will be built on top of the 5G use cases. A few extra application areas will be enabled by 5G-A, such as train networks (GSM-R replacement), enhanced capacity Non-Terrestrial Networks as well as XR (including Augmented Reality, Virtual Reality and/or Mixed Reality) solutions and use of 5G in cost sensitive, lower data rate IoT solutions.

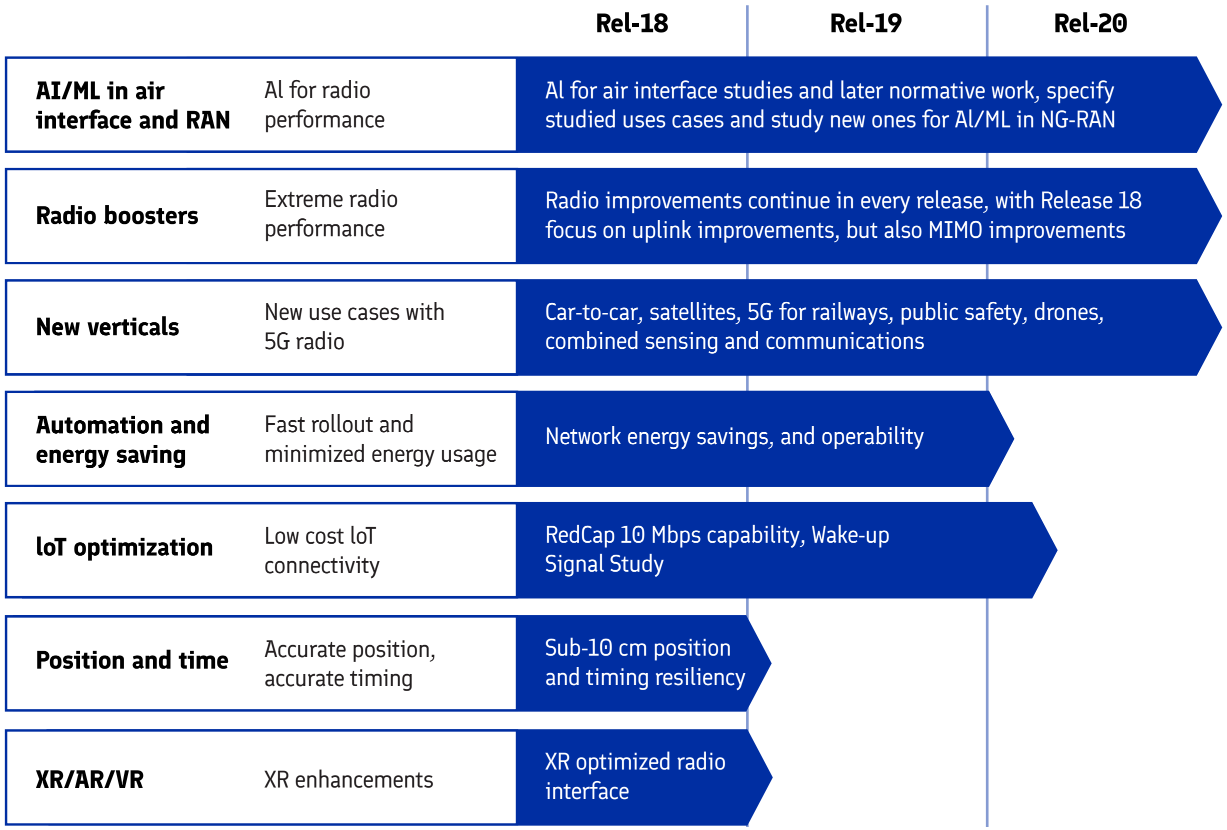
3.5 EXPECTED IMPACTS

The impacts of 5G-Advanced for societal, industrial and research can be related to 5G (see Section 2.5).



3.6 ROADMAP

The work towards 3GPP's Release 18 has just started by identifying its standardization topics. Many of the study items aim at normative work or are in requirements discussion phase and later predict actual work in Release 19 and beyond. Figure 3 shows Release 18 items having emphasis on topics expected to influence also Release 19 and beyond work for 5G-Advanced. Some items may get fully concluded in Release 19 while especially the bigger topics usually span over several Releases.



XR Extended reality
AR Augmented reality
VR Virtual reality

Figure 3. 3GPP 5G Radio standardization releases 18, 19 and 20.

4. 6G

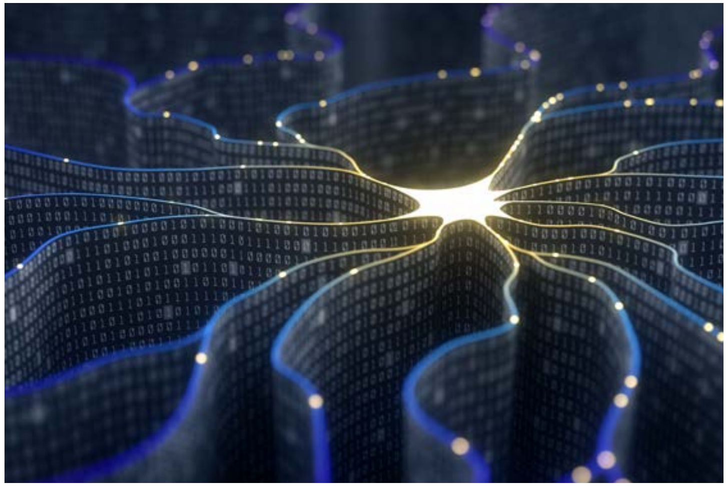
4.1 STATE OF THE ART AND FUTURE OUTLOOK

6G development has started globally and in Finland already in late 2010's. Some elements for 6G technology have been developed, for example, in European Union H2020 research and innovation funded projects (e.g., Hexa-X, DREAM, DRAGON) as well as in Finnish national projects. In the middle of 2018, Academy of Finland decided to fund 6G Flagship programme, which is one of the major 6G programmes also globally. After the academic start, major industrial players have also started their research and more recently a consortium of industry and academia have started the joint work. The only European level 6G Flagship project Hexa-X started in January 2021. After that many research institutions and companies in Finland have got engaged with 6G related research, e.g., via European Hexa-X project led by Nokia Finland. Both at national and EU levels 6G technology has been named as one of the key priority areas and several new initiatives have been launched and will be launched in the coming months. Other key regions in 6G R&D&I are Japan, South-Korea, USA and of course China. India has also made ambitious statements concerning 6G. Within EU, Germany, Spain and France are the leaders alongside with Finland and many others are expected to join very soon. Finland is in a very good position to team up with critical players globally and outside the EU Asian players are currently the most advanced in 6G development whereas USA is lagging behind.

6G is clearly in research mode until the beginning of 2025 and there is plenty of room for new ideas and innovations. For example, 2.5-year European Hexa-X project has investigated several relevant technology enablers since the beginning of 2021 and its possible continuation will start to develop the first 6G system concept at the beginning of 2023 and expect to have a full 6G system concept by mid-2025. Besides the integrated system concept, it is worthwhile to develop critical technology enablers towards 6G. However, careful and critical focusing is needed to distinguish between generic far-reaching wireless enablers and 6G enablers to be commercialized within the next 10 years. Areas like semantic communications or quantum communications go far beyond the 2030's, possibly beyond 2040's. Even THz/sub-THz communications is a border line within the 6G timeframes. We don't have yet IC technology to support it commercially within the 6G timeframe and the communication ranges at THz/sub-THz bands are less than 10 meters for mobile terminals, but up to ~ 1 km at point-to-point links in good weather conditions. From the wireless networking perspectives, the so-called "clean-slate" design is often raised but it also requires careful distinction between technologies to be realized by the early 2030's and blue-sky ideas. New approaches are needed to allow service centric networks rather than the current RAN centricity. Allowing different types of access networks to operate jointly in a technology agnostic manner would be desired, and thus, different alternatives for the local connectivity solutions need to be developed. This also leads to highly delicate issues concerning spectrum ownership and local licensing, user ownership, networks ownership, security and trust and many more, which are not technology challenges, but regulative and policy challenges. Pushing concepts similar to local 5G (Japan) are vital for 6G networks operative models. While local networks and urban areas are key development areas, also remote area connectivity using satellite constellations both for broadband and IoT services will be needed.

Additionally, and importantly, future 6G networks are expected to facilitate convergence of the next-generation data communications, high-efficiency device positioning and radio-based sensing of the environment – all integrated into the same radio network. This is commonly referred to as the integrated sensing and communications (ISAC) paradigm and is expected to be one of the major differentiators compared to 5G-based systems.

6G will play a role in truly realizing the services envisaged for 5G just as 4G enhanced the mobile broadband service introduced in 3G. We already have identified some challenges with 5G technology, such as mmWave beamforming or spectrum management between private and public 5G networks having different TDD frame configurations, that can in part be solved as 5G evolves, and should be fully solved right at the beginning of 6G development to lay foundation for new 6G applications and further system development.



The transport network that carries all the data conveyed across the radio access networks has got less attention in the 5G research. Access rates in 5G/6G are growing to gigabit per second level per user equipment, which means that the backhaul network, not to mention the core transport network, has to support Terabit (even Petabit) per second transport pipes. Paying no attention to this part of the communication network leads sooner or later to congested core transport network. In order to avoid transport network becoming a bottleneck, optical transport, network layer protocols and security issues should be researched to find viable core network solutions for the future mobile networks.

As major development is still needed for radio, radio access and core network technologies, the softwarization of the whole system will bring new challenges for the integrity, security and sustainability to 6G networks and end-to-end connectivity of users and services. We can also say that 6G and 6G businesses will succeed or fail with software. The complexity of the networks and huge systems of interconnected devices with software-based applications and services will require software development methods, tools and software architectures that do not exist today. siness models requiring field specific regulation changes; ownership of customers and networks changes.

To summarize, the following main generic challenges can be seen for 6G research:

- **Societal challenges and digital inclusion with global coverage**
  - Connectivity is key to satisfy the United Nations (UN) Sustainable Development Goals (SDGs) and needs of digital societies; current terrestrial technologies with evolutionary features need to be complemented by specific remote area solutions including satellites.
  - There are several use cases where vertical dimension is essential. Future networks should be able to provide positioning and connectivity services accurately in 3D space.
- **New ecosystems and disruptive business models**
  - Digital societies and emergence of new verticals create new ecosystems and disrupts current business models requiring field specific regulation changes; ownership of customers and networks changes.
- **Global collaboration and standards**
  - 6G coalitions forming in a new geopolitical landscape; a new standard is introduced after every 10-years – business reshaped in 20-year cycles; spectrum regulation principles changing ~25++ year cycles.
- **6G Technology enablers & challenges**
  - Data privacy and security - Expansion of verticals with new stakeholders and emergence of large number of new players providing different network elements, critical applications and operating different parts of networks sets new privacy & security requirements.
  - Service driven network architecture - Having the connectivity everywhere is needed for the smart society. Networks are ubiquitous, and can and will be built by different operators for different purposes. Local specialized services with various connectivity mechanisms are becoming more and more popular. Service driven architectures are becoming dominant after the network ownership driven era.
  - Super-efficient connectivity at high spectrum bands - Extreme speeds, reliability, low latency and localization/sensing accuracy can be achieved only locally in rather short-range networks utilizing the higher frequency bands even above 100GHz.
  - Advanced ground segments able to connect both to terrestrial and non-terrestrial platforms – Developments are needed in antenna technologies, network protocols, and standardization to truly integrate non-terrestrial systems into mobile networks.
  - Smart AI/ML enabled networks and services - Networks and applications become intelligent, self-learning and context dependent; edge intelligence is the key technical enabler and challenges/complements centralized cloud solutions.
  - New methods and tools for developing, deploying and maintaining massively distributed heterogeneous software systems, applications and ecosystems.

4.2 STRATEGIC OBJECTIVES

To tackle the generic 6G challenges, the following technology areas need to be investigated:

1. Wireless connectivity, positioning and sensing solutions
2. Device and circuit technologies
3. Distributed intelligence and software in mobile networks
4. Software methods tools and architectures

In the following, some key research and development areas have been identified for the aforementioned technology areas.

1. **Wireless connectivity solutions have the following main themes with some more detailed areas to be investigated:**

   Future networking technologies; including, e.g., 6G core and telecommunication cloud solutions, edge cloud solutions, AI driven networking solutions, end-to-end security/trust/dependability enablers, end-to-end resource optimization and sustainability of mobile network, new architecture solutions for radio access and core network, secure backbone and Internet connectivity, automation and zero-touch of service and function orchestration and provisioning.

   Wireless access technologies; including, e.g., (dynamic) spectrum access including high spectrum bands, MIMO solutions with low complexity and low energy consumption, new RAN architectures including Reconfigurable Intelligent Surfaces, 3D networks with aerial and space platforms, moving RAN, etc., integrated communications and sensing systems, waveforms, modulation, coding and other PHY layer technologies, signal processing and algorithms for future RAN

   Wireless solutions for massive automation; including, e.g., massively deployed ubiquitous IoT, critical machine type communications (MTC), short range low-power 'in-X' subnetworks for reliable MTC for automation and automotive applications, sustainable wireless MTC including zero power devices and energy harvesting, interference and spectrum management between private industrial and public MNO networks

2. **Device and circuit technologies can be broken down to the following challenges:**

   Radio platforms; including, e.g., radio system design from HW perspectives, HW architecture (MU-MIMO, large-scale arrays, modularity), baseband and signal processing

   Radio Hardware; including, e.g., RF IC technologies, DSP hardware, components, antennas, packaging, materials and fabrication technologies, integration technologies, sustainable hardware (sustainable manufacturing & printed electronics, e-waste minimization)

3. **Distributed intelligence in mobile networks has the following main areas to be considered:**

   Mobile edge cloud; including, e.g., functionalities for improving RAN capabilities, near real-time AI solutions – small data approach.

   Distributed AI; distributed inference. privacy preserving AI, Security of AI, Software for highly distributed heterogenous massive networks of connected devices.

   Distributed sensing; coordinated sensing & communication, multimodal 3D environment modeling.

4. **Software methods, tools, and architectures – areas to be considered:**

   6G software – extremely distributed environment; including, e.g., software for highly distributed heterogenous massive networks of connected devices, software-based architecture solution evolutions for 6G architecture, trustworthiness and security of 6G software, virtualization platforms, "agent"-based software software solutions.

   6G software quality and sustainability; including, e.g., maintenance, operational, NFR and long-term sustainability of 6G software.

   6G era software tools; including, e.g., tools for development and maintenance of real-time software and environments within and between 6G devices, edge and cloud.

   6G software applications; including, e.g., apps from Micro to Macro, from mesh-apps at real-time proximity to device-edge-cloud continuum, in-network applications. 6G applications and services will be based on software. They range from simple apps to large platforms and ecosystems. They need to take advantage and run on the 6G infrastructure. The success of 6G as a business area depends on these software-based applications and services.

5. **Future services and business models enabled by regulation should consider;** for example, future 6G enabled business, sustainable development and 6G, regulation for 6G, new use case requirements and design, network KPI and KVI specification for future services.

4.3 IMPLEMENTATION CHALLENGES

The main challenge is to ensure smooth transition from 5G and 5G-Advanced to 6G without sacrificing too much technical capabilities for maintaining constant evolution. **The introduction of the high spectrum bands at 100-300GHz is probably the greatest technical implementation challenge.** Also, **allowing operation of various alternative RAN solutions tailored for different verticals locally** is another challenge: how much customization can the standards allow without diversifying too much. Similarly, can we allow proprietary solutions for some special use cases? Yet another challenge is to allow dynamic spectrum usage/allocation: can we finally realize comprehensive spectrum sharing allocation schemes locally at mmWaves and above. **The biggest fear related to 6G is the overall technology acceptance:** if we cannot guarantee absolute security and privacy, the user will not build any trust on 6G. **How can we implement privacy preserving data sharing to implement future AI driven services** is one key question. One everlasting challenge has been how to incorporate the non-terrestrial component to be part of the overall mobile network. This issue can be expected to be on the drawing desks also during the 6G development. Especially interesting are large satellite constellations operating in the low Earth orbit (LEO) - and what kind of ground segments are needed to support multi-layer networking. In addition, **software is in a very central role for future communication networks.** The number of connected devices is expected to explode, and they all have software. They range from micro-level devices with very limited processing capability to larger connected devices with strong processing power and up to large applications in the cloud. The software development for these complex, heterogeneous and highly distributed systems require novel architectures, methods and tools. **An important aspect is the quality and long-term sustainability of the software.** Companies are wasting huge amounts of money because the software was not built with a long-term maintenance priority. Considering the high number of changes that the 6G management software will need as complexity of the system and automation for management increases, it is important to develop software maintenance, quality, and software architectures, as well as the software and service orchestration and provisioning models.

4.4 APPLICATION AREAS AND USE CASES

Besides the existing and 5G enabled applications and use cases, some new application areas and use cases are of importance. These include for example both o**pen and private local networks with highly customized services** needing highly customized RAN solutions. This has an impact, for example, on RAN and Core network architecture, performance and reliability as well as AI based management of 6G system. **Massive twinning** will also be of interest and importance. This is considering the support for creating digital twins and to model physical world in extended fidelity and scale, compared for example to industrial twinning introduced by 5G. In addition to telecommunication application areas like industry, healthcare, food production, smart cities, etc., the digital modelling and real-time interaction between digital representation of holistic network system and real-world deployment would be of interest. **Realistic telepresence** and support for immersive experiences through for example avatars are also seen as one breakthrough applications for 6G. Massive twinning, real-time and seamless interaction with real and virtual objects and mixed reality co-design in anywhere/anytime will be the key functions for mobile metaverses, whether they are global, local or application domain specific (industrial, military, health-care etc.). The plethora of IoT nodes supporting the environment and systems management, monitoring and control will be power hungry and challenging to maintain. Thus, for different application areas and use cases, the **"everlasting" IoT nodes with energy harvesting capabilities,** are needed. How the 6G can support such features from hardware and software point of view, is one of the key research questions. This applies also to so called bio-nano-things, i.e., nano-scale biological computing machines collecting sensory data from biological organisms, and which are connected and interacting with telecommunication systems and the Internet. The fifth main use case area can be described as **situational awareness for rapid decision making.** This can be seen to relate also in several application domains, from emergency to industry, and requires various features mentioned above, but also extended reliability and trustworthiness of data collection and connectivity platforms. In addition, as AI/ML nowadays, robots are foreseen to be a more integral part of our society in the near future. The capabilities of industrial robots in manufacturing, healthcare robots in hospitals or pharmacy, consumer robots at home and offices, and various robots and autonomic vehicles in traffic, are gradually increasing. Robots will become more and more responsible, carrying out more complex tasks. This will require more and more collaboration between other robots and especially with humans, implying a new generation of highly interacting and cooperating mobile robots, i.e., **collaborative robots** (cobots). The 6G is a key enabler also for cobots, requiring high performance, security and dependability from 6G system. Regarding 6G airborne networks, two interesting use cases include **Flying Base Station Networks** and **Air Mobility Networks.** The former aims to primarily serve ground users that do not obtain sufficient performance for the terrestrial network while the latter is a new network paradigm serving all aerial machines flying between the ground and 20 km altitude. This Air Mobility Network provides control and communication services for example, for UAVs, air taxis, balloons, and aircraft. In addition to air-to-ground and ground-to-air communications, also device-to-device and sidelink communications are key features for the 6G airborne networks. Drones also need a reliable data link for command and control and to enable high resolution real-time data feed (from its sensors). Additionally, drones themselves can also work as relays for extending the network coverage.

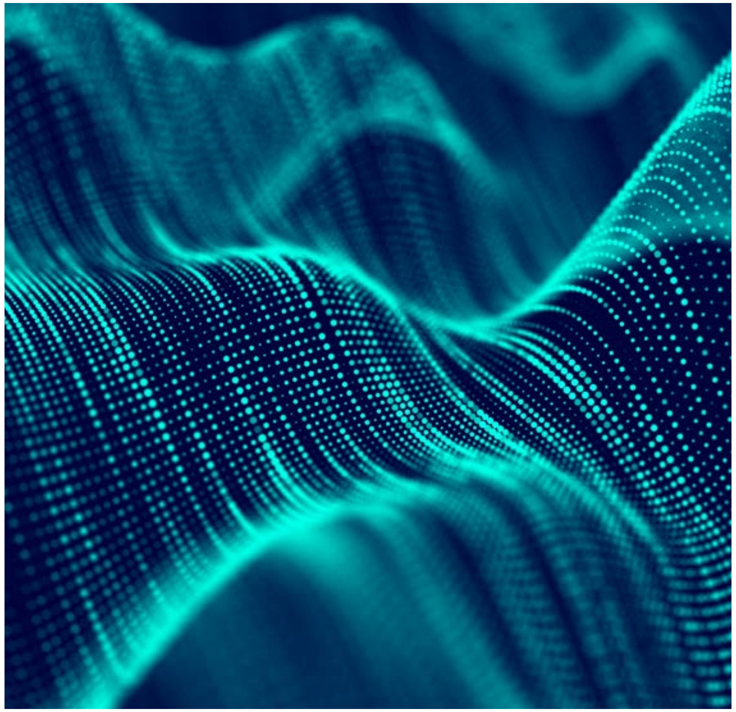
4.5 EXPECTED IMPACTS

Finland was the first country in the world to start 6G research and development work through Academy of Finland initiated Flagship project. Carrying out the national 6G research enable Finnish 6G R&D community to keep its leadership position also in global scale. Focusing and extending the national far-seeing 6G research work will have, not only impact to academic career and excellence / know-how development, but also in creating new Finnish innovations and boosting the industry by enabling IPR development. As a summary we can identify, e.g., the following milestones, even before realization and deployment of the first 6G systems:

- 400 new 6G experts have been trained within the BF funded projects by the end of 2026
- 250 6G IPRs have been transferred to Finnish industry by the end of 2026
- Finnish players have participated in 50 EU SNS projects by the end of 2026
- All Finnish wireless research groups have increased their visibility, impact and quality; Finland has become one of the most attractive places for international students in Europe

4.5.1 SOCIETY

In addition to performance boosting, one of the key targets for the 6G system is to provide a secure and sustainable platform for cross-sectoral innovations. These innovations and cross-sectoral application areas can include for example smart cities, people flow, traffic, safety and security, education, and in more generally digitalization of modern networked society. The technological advances for 6G are foreseen to increase productivity and to minimize the operational as well as capital expenditures for ICT. From national point of view, the investments to maintain and improve our leading position in telecommunication and network system development, can bring benefit for society by, e.g., through increased number of new workplaces, IPR income and business around 6G and its applications.



4.5.2 INDUSTRY

One of the most important impacts from 6G research and development for industry is to empower intellectual property development. The new innovations from research for both core communication technology as well as novel applications are foreseen to boost also Finnish industry. Opportunities arising from open system interfaces, virtualized software functions and in-network applications, network software and hardware development needs, and advanced application development for vertical industry, can open opportunities also for new small and medium size enterprises.

The improved performance, reliability, trustworthiness and sustainability will, on other hand, provide better solutions for telecommunication and network technologies vertical industry. Including for example industrial systems, manufacturing, facility repair and maintenance, etc.

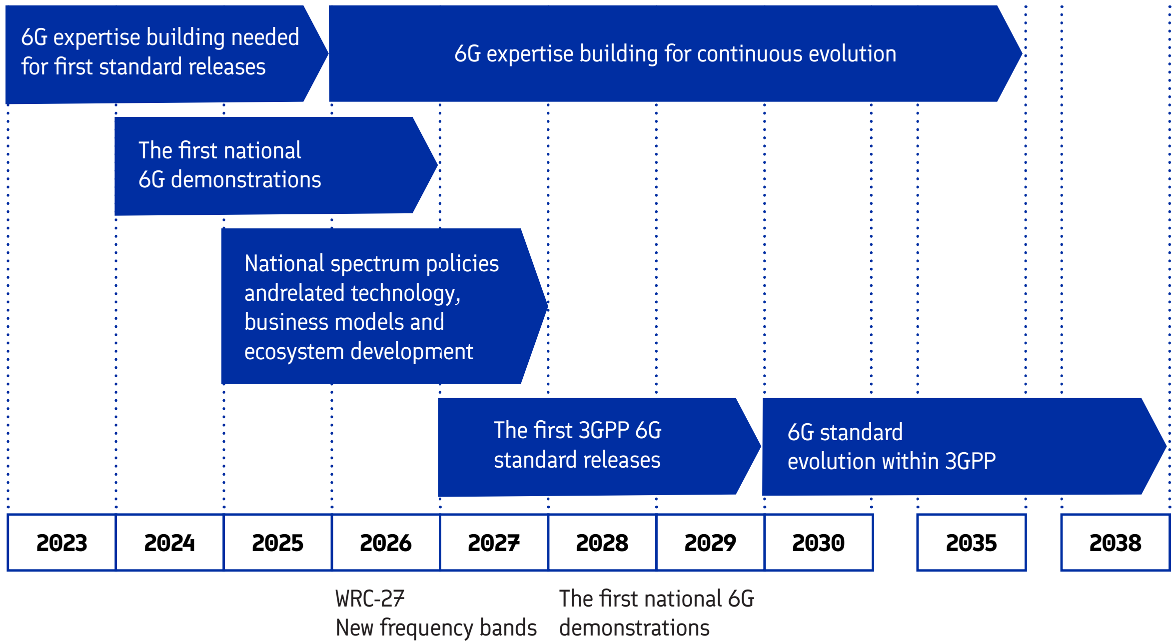
4.5.3 RESEARCH AND ACADEMIA

As for 5G and 5G-Advanced, the 6G research educates new telecommunication system experts, software engineers, and AI experts for ICT technology field. From the Finnish industry and economics point of view, it is important that also in the future Finland can provide highly educated people to the work market and attract new talents to work in Finland. The top-notch 6G research, with increased visibility of R&D, will be a key to attract top experts.

4.6 ROADMAP

Early start is vital in 6G expertise development, therefore, research activities towards 6G need to be started from the beginning of 6G Bridge. It is also important that the European 5G PPP and SNS JU 6G Flagship projects' timelines are aligned with national activities. Therefore, the first technology selections with small scale selected demos should be carried out after two years of 6G Bridge operation, i.e., well before 6G standardization is expected to start in 2026.

The next World Radiocommunication Conference (WRC) after the one to be held in 2023 is currently scheduled to 2027. Therefore, national frequency policies towards 6G as well as fundamental technology knowledge must be systematically developed in the meanwhile. With this reasoning, the national roadmap towards 6G could be the following:



2023 – 2025	**6G expertise building needed for the first standard release;** to lay the foundations for 6G basic system, standards, and first national 6G demonstrations etc.
2024 – 2026	**The first national 6G demonstrations;** demonstration of potential 6G technology enablers and sytem components, definition of end-to-end system KPI/KVI validation criteria etc.
2025 – 2027	**National spectrum policies and related technology, business models and ecosystems development**; technology development, setting national spectrum policies, contributions to global 6G regulations and further development of national ecosystem etc.
2026 – 2028	**6G standard first version within 3GPP;** contributions and development of first 6G standards, enhance ment of national 6G demonstration capabilities and use case demonstration of 6G basic system etc.
– 2035	**6G expertise building for continuous evolution;** building the expertise for 6G evolution, technology enabler development, research of use cases etc.
– 2038	**6G standard evolution within 3GPP;** contribution to standardization, development of technology enablers etc.

5. TEST ENVIRONMENTS

5.1 STATE OF THE ART AND FUTURE OUTLOOK

Existing test environments can be roughly classified into three categories; industrial environments based on commercial and pre-commercial 5G technology, 5G evolution-based research testbeds and test environments for 5G Advanced and 6G experimentations.

5.1.1 INDUSTRIAL ENVIRONMENTS

Existing 5G network deployments are assuming primarily downlink traffic model and targeting to improve personal (video/data) services, i.e., smooth mobile broadband experience for human-to-human or human-to-machine use. Some services combine 5G connectivity with some other asset, like positioning information, and overlay positioning-networks may be installed for (indoor) locations with no GNSS service.

Networks in Finland are typically operating on n78 band (3500 MHz 5G band). New frequency bands have been allocated for regional/local use to support also private 5G networks with tailored services and terminal types. UEs particularly for industrial use are entering the market, but selection is still limited.

Industrial & academic test environments are used for validating the mobile technology for new use cases and for ensuring E2E operations (and technical maturity) including network, user device, related services and UI. Experimentation reveals details also for performance helping analysis of economic feasibility, and it boosts the collaboration between industry and academic research. These assets and related collaboration model are assumed to continue, thus smoothening the evolution from current 1st wave 5G towards 6G.

An important aspect is the quality and long-term sustainability of the 5G/6G software. Companies are spending huge amounts of money because the software was not built with a long-term maintenance priority. Considering the high number of changes that the 5G/6G management software and vertical applications will need, it is important that test environments and testbeds take into account software quality, testing and maintenance.

5.1.2 5G EVOLUTION-BASED RESEARCH TESTBEDS

The testbeds for 5G evolution outside Finland have been developed mainly by PPP projects. 5G Infrastructure PPP Phase 3 platform projects (2018-2021) provide a pan-EU large-scale end-to-end 5G validation network infrastructure, covering about 20 EU sites and nodes on a pan-EU basis. This infrastructure provides the openness to make it possible for vertical industries to test their innovative 5G business cases using ad-hoc network resource control in an end-to-end interoperability framework. The key capabilities and features of the PPP Phase 3 platforms include among others Rel15-5GNR in Non-Standalone (NSA) mode, Rel15-5GNR with Rel15 5GCore in Standalone (SA) mode, Rel16-5GNR and 5GCore (NSA or SA), Network Slicing as a service, Customized network slice (e.g., SFC, security, enhanced Cloud access), Edge Computing, Distributed Data fabric service for analytics, 26 GHz 5G Radios and millimeter wave based solution for backhaul.

Also, Finnish research organisations and industry have during years 2017 – 2021 designed and implemented 5G Test Network Finland (www.5gtnf.fi) ecosystem and multi-site test environment supporting 5G technology research and validation, vertical industry product development and pioneer company experiments. The current implementation is mainly based on 3GPP/Rel-15 specifications. 5GTNF includes multiple 5G technology and service development platform with a continuously evolving Radio Access Network (RAN) and a cloud-based Core Network. The RAN part contains both 4G (LTE-A) and 5G technologies for flexible utilisation in a variety of use cases. The core network parts are fully virtualised, supporting distribution of network functionalities in both control plane and user plane. All test network sites include also Multi-access Edge Computing (MEC) functionality for shifting e.g., heavy computing into the network edge as well as diminishing the user delay. In addition, the testbed sites have an integrated testing and network management frameworks implemented, enabling new functionalities in these domains to be built on top of the existing platform or as parallel implementations complementing the existing functionality.

5.1.3 5G ADVANCED AND 6G TEST ENVIRONMENTS

There is also running several big 5G Advanced and 6G research activities (e.g., 6G Research Hubs in Germany, UNICO I+D in Spain and 6G Flagship in Finland) with much more focused prototyping environments for 6G key concepts and technologies; 6G sub-THz transceivers, digital signal processing solutions for THz communication, reflective intelligent surfaces, distributed network control and edge AI solutions and enhanced localization, sensing and imaging.

Lessons learnt during the development of previous wireless and mobile communication generation test environments and vision about future requirements can be summarized as following R&D&I challenges:

- Risks related to commercialization of new technology. This risk can be mitigated by early experimentation of new innovations at available test platforms.
- Continuation of world-class Finnish ICT research need to be secured by further developing national test infrastructures and utilizing also previous investments.
- New services and use cases need to be globally scalable, backwards compatible with previous technology generations, and integrated with possible use-case specific standards and practices. This requires collaboration between European and national activities.
- Network evolution will trigger new use case opportunities. Feasibility of solutions can be confirmed only with experimentation. Companies and research organizations need possibilities to utilize world class development environments.
- Many current industries are slow-moving and do not have enough knowledge about possibilities provided by recent technology and digitalization. There is a constant need for innovative solutions visible for various use cases.
- ICT sector attractiveness, and new engineers with the right skills. Using academic test environments during engineering studies should be a natural part of courses as lab-exercises, project work and thesis.

5.2 STRATEGIC OBJECTIVES

Based on the state of art status and identified R&D&I challenges, following strategic objectives are set for national research and innovation activities:

1. Development of test environments which allows rapid evaluation of 5G evolution, 5G Advanced and 6G service concepts, technologies, system solutions and business models, at a level that minimizes risks related to introduction of commercial services and products.
2. Reusability and evolvability of the test environments over the lifetime of the national and European programmes (BF 6GBridge & 6G, Horizon Europe/SNS, Digital Europe TEF, 6G Flagship, ...) and 5G/6G standardization (3GPP, ORAN, IETF, ETSI, IEEE, ...), accessibility, and openness, and optimization of previous and related investments in Finland, friendliness to disruptions and support to E2E demonstrations.
3. Validation of core technologies and architectures in the context of specific vertical use-case implementations and relevant deployment scenarios. Use cases should be tested and validated across a multiplicity of industrial sectors and including also innovative 6G applications.
4. Update of 5G Test Network Finland (5GTNF) ecosystem and testbed towards 6G era.

5.3 IMPLEMENTATION CHALLENGES

General challenge is to find practises for testbed specification, design, management, and utilization and use of national resources, which enable competitive advantages inside Europe and globally. The main competitors have (Europe, Asia, USA) have much more resources than Finland. So, the key question is how to utilize Finnish resources in maximal way. Solutions are needed for:

- Confirmation of maximal synergy between different actors (industry, research organisations, authorities) and different test environment development activities in Finland.
- Creation and utilization of synergies with other national (Academy of Finland), European (EU SNS JU, Digital Europe TEF, Chips Act), Asian and American activities. For example, European Chips Act initiative plans to allocate 4 billion Euros for chip technology development to promote self-sufficiency and independence.
- Definition of national priorities and main responsibility areas for each public research organisation.

Usefulness of test environments depends on support to different user group demands and features beyond commercial technologies. Start-ups, SME's, midcaps, and large companies have often different R&D and business development goals and time spans. In addition, network manufacturers, operators, technology, and R&D service providers, testing systems and tools, applications developers, public organisations, and research organisations may give highest priorities to different type of use cases and test environment features. To support all these user groups, we need proactive and open information sharing about test environment future requirements with standardisation activities (3GPP, O-RAN, IETF, ETSI, IEEE, ...) and American, Asian, and European research activities.

To maximize the test environment impact to the Finnish industry and society, we should confirm test environments openness and accessibility. There is need to support at same time company specific confidential product and business development goals and enable wide impact by sharing maximal amount information about test environment architecture, interfaces, and technology details. Human resourcing of research test networks management and maintenance is often big challenge in practise. In addition, we should clarify business incentives and models for shared test environments and practises for resources, costs, information sharing between co-operating sites.

5.4 APPLICATION AREAS

Industry digitalization, climate change mitigation activities and accelerating urbanization lead to increasing need for more high-performance communication and automation technologies, devices, systems and solutions in societies and industries. 5G Advanced and 6G technologies will provide needed performance for several application areas: process and manufacturing industry, machines, energy: mobility and transport, health and wellbeing, public safety, and building and living areas.

5G Advanced brings improvements in many areas, and these capabilities need experimentation and trailing before assuming global deployments. Some improvements are relevant to overall system performance, operational efficiency and sustainability, like uplink coverage & MIMO enhancements and network energy saving capabilities. Some enhancements, in turn, help investigating new use cases and services, like synchronization resiliency, XR and positioning accuracy enhancements.

Also new business opportunities are evolving by spectrum sharing enhancements, RedCap optimizations for IoT and e.g., GSM-R migration to 5G.

5.5 EXPECTED IMPACTS

5.5.1 BUSINESS

Digitalization is completed on those sectors, which do not have physical products to be delivered, like finance/banking, insurance, travel-arrangements, and entertainment music/movies. Majority of the businesses are still missing this economic boost due to physical nature of the business, and long-life cycle of investments. However, these businesses represent much bigger share of GDP than digital industries.

There's still long way to go before all 5G promises are fulfilled.

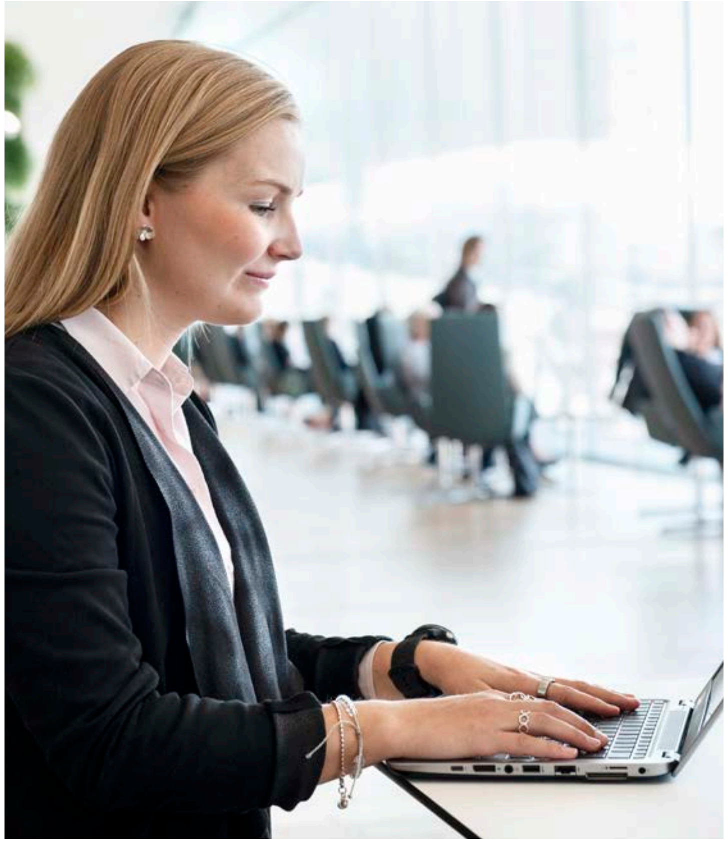
5.5.2 SCIENCE AND TECHNOLOGY

Development towards the 6G system architecture is progressing through three parallel and complementary deployment paths: 3GPP (Rel17-20), O-RAN and disruptive 6G paths. New innovations will cover radio access, network control, user equipment, testing tools and applications utilizing remarkably improving performance of communication systems. Implementation reusable and evolvable of the test network promote the progress of 6G technology research and development by enabling rapid evaluation of 5G evolution, 5G Advanced and 6G service concepts, technologies, system solutions and business models.

5.5.3 SOCIETY

5G Advanced and 6G communication network will be the backbone and key enabler of future societies. Focused research and innovation (RI) investments will enable the creation of a competitive development environment for future communication technologies and solutions. Results will renew Finnish test network infrastructures and related co-operation processes by considering new network architectures and technologies and new vertical industry needs. In addition, RI investments will increase co-operation between research organizations and improve industry's possibility to utilize new technologies and increase their own related RI investments. Results will also improve research organizations and industry possibility to participate in related EU programs and innovation and value networks. All these benefits will increase competitiveness of Finnish society.

At global level, through improved performance and resource efficiency of communication infrastructure and applications, the RI investments have positive impact especially on United Nations SDG (Sustainable Development Goals) goals number 9 (industry, innovation, and infrastructure) and 11 (sustainable cities and communities). The SDG9 is supported by enabling resilient infrastructures, promoting inclusive and sustainable industrialization, and fostering innovation. Correspondingly SDG11 is supported by enabling inclusive, safe, resilient, and sustainable cities and human settlements.



5.6 ROADMAP

To respond the identified challenges and achieve the defined objectives, research and innovation activities should focus on themes described in the table on the next page.

THEMES/TIMING	YEARS 2023–2024
Industrial IoT	• Telecom technology enablers and PoC for test environments; 5G, 5G Advanced and 6G radio access, radio and core network control, user devices, antennas, RF, digital HW & SW, NTN, network security, E2E networking solutions including routing protocols. • Support to innovative 5G-Advanced and 6G use cases; internet of senses, reflective intelligent surfaces, utilization of 3D Digital Twins, transfer of holograms, metaverse, …
Test bed functionality, architecture, and technologies	• Improvement of test environments usability, flexibility, openness, accessibility, and support to disruptions and E2E demonstrations • Support to open data sharing • Testing tools; emulators, trouble shooting, fault diagnosis, software testing methods, tools and processes, … • System simulation environments • Hybrid test beds based partly on physical prototypes and partly on digital twins of physical parts • Enabling the validations of significant improvement of key parameters like energy consumption (equipment and software) • Integration of test environments and update of 5GTNF infrastructure towards 6G era
Trials and pilots	• Implementation of large-scale vertical use case trials with 5G Evolution technology • Validation of KPI's and KVI's in the context of specific use case's • Promoting and validating energy efficiency and sustainability solutions in the ICT sector
THEMES/TIMING	**YEARS 2025–2026**
Test bed enablers and PoC's	• focus on 6G technologies and application enablers • quantum communication technologies and solutions
Test bed functionality, architecture, and technologies	• utilization and integration of EU's SNS JU phase 1 and Digital Europe TEF projects results • development of detailed and comprehensive simulation models about whole product/system; digital twin about B5G/6G network with applications instead of system prototype
Trials and pilots	• utilization and integration of EU's SNS JU phase 1 and Digital Europe TEF projects results • development of detailed and comprehensive simulation models about whole product/system; digital twin about B5G/6G network with applications instead of system prototype
THEMES/TIMING	**YEARS 2027–2030**
Test bed enablers and PoC's	• focus on 6G evolution technology and application enablers • utilization of quantum computing in telecom system design and implementation
Test bed functionality, architecture, and technologies	• utilization and integration of EU's SNS JU phase 2 and Digital Europe TEF projects results
Trials and pilots	• utilization of 6G technology in-large scale trials of 6G use cases like metaverse

6. OVERALL ROADMAP

6.1 INTERNATIONAL ACTIVITIES AND ROADMAPS

The European 5G Public-Private Partnership initiated the first 6G research projects at the beginning of 2021, still within the Horizon 2020 Framework Program. A total of nine R&D projects were launched including Hexa-X Flagship project. These projects target to define the initial vision of system and technology enablers for future 6G. At the end of 2021, a new joint undertaking partnership program was launched within Horizon Europe for network and telecommunication system R&D&I. The established Smart Networks and Services Joint Undertaking released the first call for 5G evolution, 6G, and test and experimentation platforms at the beginning of 2022. While writing this document, the evaluation for the first set of projects has been carried out and projects are under contractual negotiations. The phase 1 projects are expected to start in January 2023. Total budget of the whole SNS JU is 1800 Million euros (Me), including 900 Me public funding and 900 Me private funding. The contractual partners are the European Commission from the public side and the 6G Industry Association (6G-IA) from the private side.

The SNS JU work program was based on the strategic research and innovation agenda provided by NetworldEurope ETP. The SRIA work was carried out during 2020 including contributions from over 90 organizations and 150 individual contributors. The SRIA document can be downloaded from NetworldEurope's web pages[3]. The SRIA focuses on nine key technology areas for future smart networks and services. These are namely,

1. **Human Centric and Vertical Services;** considering for example digital service transformation, extreme automation and real-time zero-touch service orchestration, and emerging applications and use cases
2. **System Architecture;** including system architecture vision towards green and sustainable system, AI/ML-based system evolution, programmability, and multi-tenancy
3. **Edge Computing and Meta-data;** focusing on distributed services, computing platform and, e.g., virtualization, and edge AI continuum
4. **Radio Technology and Signal Processing;** including, e.g., mmWave systems, terahertz communication, massive and ultra-massive MIMO technologies, optical wireless communications, spectrum re-farming and reutilization etc.
5. **Optical Networks;** considering for example sustainable capacity scaling, new switching paradigms, optical network automation, and energy efficiency
6. **Network and Service Security;** focusing on system-wide security challenges, green security and security as a service, AI for security, and for example distributed ledger technologies etc.
7. **Satellite Communications Technologies;** including for example software defined payloads, spectrum usage, optical based satellite communications, antenna technologies etc.
8. **Opportunities for Devices and Components;** including RF and antenna technologies, mmWave and THz solutions, baseband modems, hardware for security, cloud/edge/on-device -AI processors etc.
9. **Emerging Technologies and Challenging Trends;** considered wide range of emerging and new technologies from nano- and bio-nano things to quantum networking, and evolution of protocols.

[3] https://bscw.5g-ppp.eu/pub/bscw.cgi/d367342/Networld2020%20SRIA%202020%20Final%20Version%202.2%20.pdf

One of the key technology and development roadmaps with which also Finnish national roadmap is aligned, is the European 6G R&D roadmap, in order to find the nationally important development focus areas. The European vision and roadmap are also highly promoting sustainability and trustworthiness of future communication systems that are also the key values for our national 6G R&D approach. Currently, the next SNS JU calls are planned for 2023, including some of the gaps identified in the first 2022 calls. The new work program is currently under work as the new release of NetworldEurope SRIA document, which is planned to be published around October 2022. It is foreseen that work in the second 2,5-year phase of SNS JU 2024-2026 will focus mainly on 6G R&D.

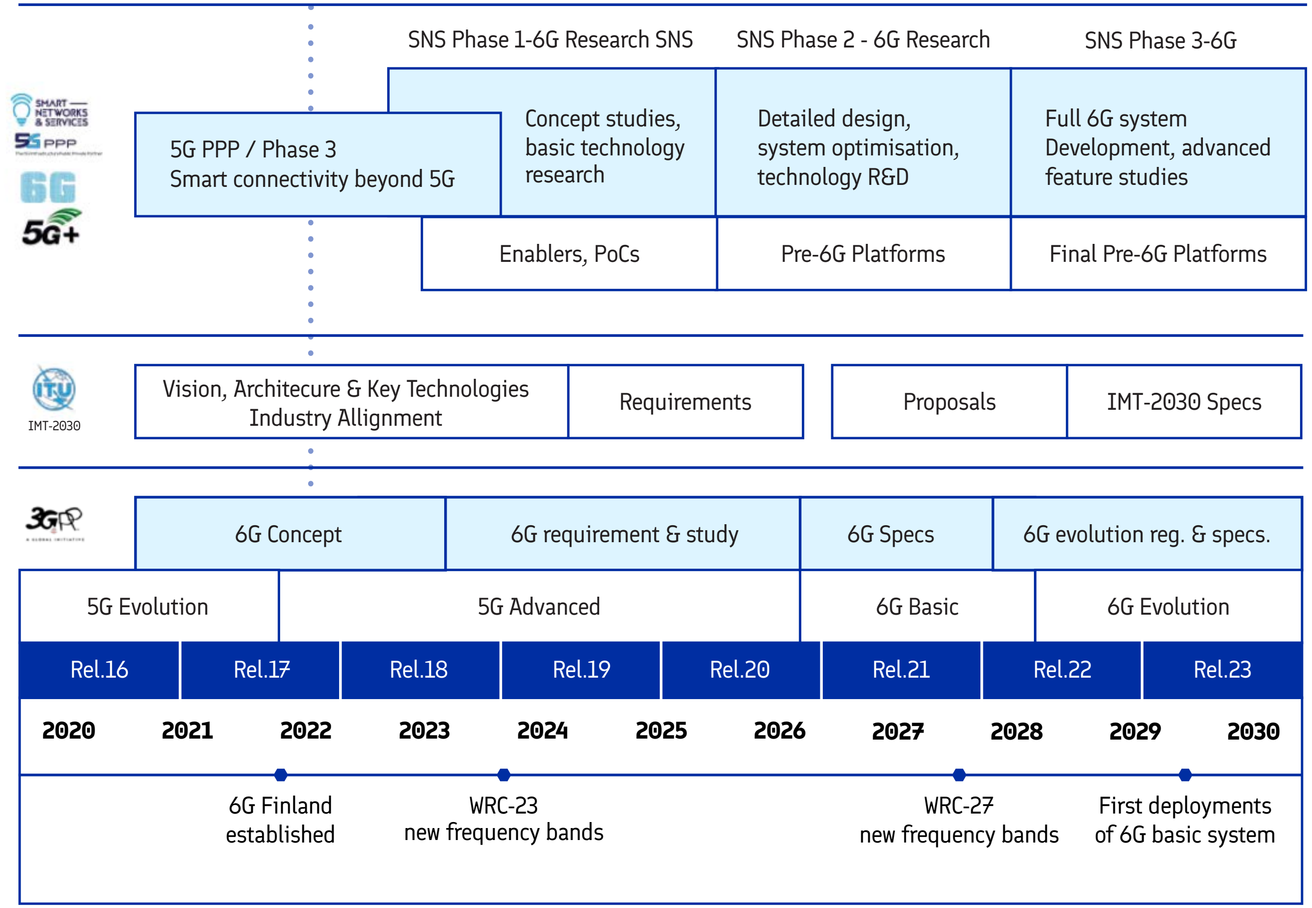


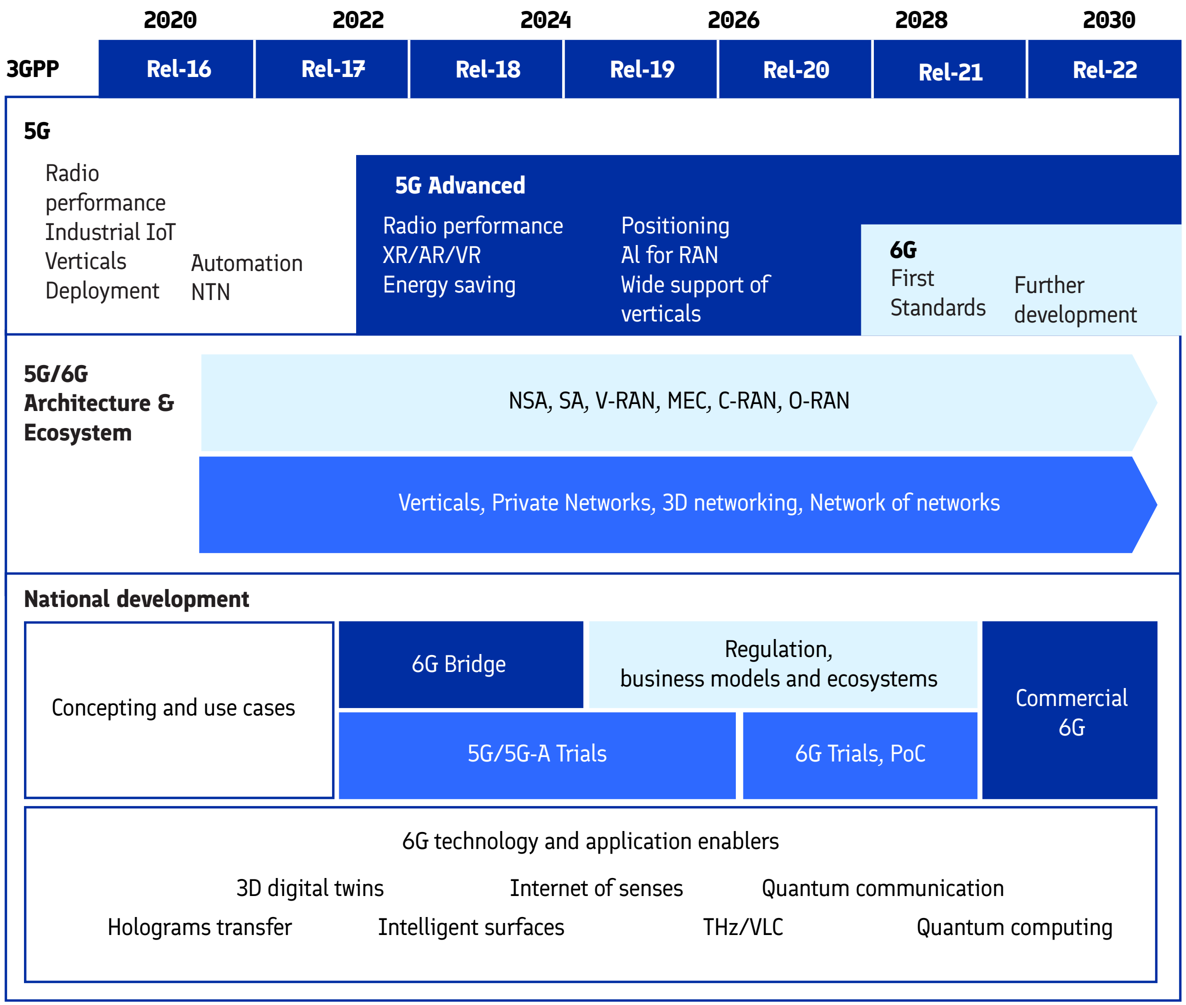
Figure 5. Indicative schedule for Smart Networks and Services in relation to ITU roadmap and 3GPP standardization

During the past year, several EU member states have started national initiatives and allocations to fund 6G R&D. These initiatives are focusing, especially, to support the evolution of 5G system and development of 5G application areas, but also to support the academic, visionary research for 6G.

In different EU member state initiatives, energy efficiency and sustainability can be seen as common themes. The aims include for example to enable energy efficiency, power savings and carbon neutrality in the overall network system design principles, devices and software, and to enable extended life-cycle of system and energy efficient use of the mobile system resources and applications in different vertical application domains.

The first German 6G research initiative was launched in April 2021 to support the national 6G research and development. For a period of five years, about 700 Me has been allocated for 6G R&D, with the main target for the first funding period to create the basis for national 6G innovation ecosystem. This includes establishing 6G research hubs, enabling collaboration between the various research institutes and universities. The focus is to carry out the R&D for 6G mobile system and optical fiber networks required by mobile network systems. In addition, the initiative targets to establish an umbrella platform project to coordinate the activities and to support for liaison in Europe and globally, including the contributions to regulation and standardization. France has also announced in 2021 to support especially the 5G evolution, focusing on future system research and development, and boosting the national 5G and telecom network solution development. A total of 733,6 Me of public funding was reserved for different activities for duration from 2022 to 2025. One key focus area in France is to support for the 5G use cases development from French national, regional and industrial benefit. The focus areas include also the strengthening of education. In addition, the private funding share of 969,6 Me was expected enabling the total of ~1700 Me financing. In Spain, alignments to support Spanish ecosystem for 5G / 6G with direct funding were made in 2021. The Council of Ministers approved in November 2021 more than 95 Me to support 5G and 6G research. The funding support is targeted for research centres, public research foundations and Spanish public universities.

In addition, the European Space Agency (ESA) has already been driving for several years the development of Non-terrestrial network development, HAPS and satellite constellation development. The Non-terrestrial networks and satellite constellations in LEO orbits consisting of hundreds to thousands of satellites are extensively developed and used for broadband connectivity globally. Commercial proprietary systems such as Starlink and Oneweb can provide backhaul connections to 3GPP networks already now. China is actively building their own constellation. The NTN development is continuing from Rel. 18 onwards, including direct connection between a handheld and a satellite. The most important European initiative to support our sovereignty is the Secure Connectivity programme, aiming to implement a multi-billion flagship satellite system to provide uninterrupted access to secure and cost-effective satellite communication services. The multi-layer system should become fully operational by 2027. Thus, there are plenty of opportunities for Finnish industry as well.



6.2 SUMMARY OF SRIA ROADMAP

Figure 5 depicts the roadmap of the national SRIA. The roadmap towards commercial launch of 6G and the subsequent development is based on preceding standardization releases as well as the continuous evolution of technology and application enablers. The global standard and regulatory processes will support the introduction of new mobile technology generations together with necessary support for legacy technologies. The formation of 6G technology is also affected by the mobile network architecture and ecosystem development. The RAN architecture evolves over time offering new possibilities of introducing new open interfaces and network softwarization. Individual mobile networks will have different evolutionary paths depending on the choices and needs of the operators. The popularity of private networks increases also in future, the privacy, security as well as performance and customers' individual needs being as main drivers. These aspects will be addressed in the National SRIA roadmap, as well. The new use cases will be based on various technological enablers, the figure showing only some of those.

The 6G Bridge Program lays the foundation for national 6G projects and cooperation. Together with the program there is continuous development of national 5G test environment ongoing concentrating on increased support for operational flexibility and 5G-A/6G technology enablers. Equally important to technology development is to continue the enhanced cooperation with 6G stakeholders. In addition to industrial and academia members the collaboration will also include government and communities ensuring regulatory and business support in various segments of society, for example communications, traffic, healthcare, security, and defense. The functions supported by 6G will not cover only communication but widely almost all aspects of modern society supporting a sustainable and more prosperous digital future. It will be a crucial part of Europe's digital transformation by 2030, aligned with the vision of the European Commission.

The 6G trials will utilize the pre-standard or first standards-based products in large scale trials of 6G use cases like metaverse. The commercial 6G networks will be deployed around 2030.

7. CONCLUSIONS

In this document we present a Finnish national research and innovation agenda and roadmap towards 6G, the sixth generation mobile networks. The SRIA document illustrates the main development targets for 5G, 5G-Advanced, 6G, and test environments. In addition, the document provides the referential roadmap for the 6G Bridge program. The SRIA and roadmap document was built by ecosystem of Finnish industry and academia, consisting of globally acknowledged technical leaders in 5G and 6G research and development.

The 6G research community has already started to develop technology foundation, requirements and enablers for 6G applications and use cases. The first technology demonstrations are expected to see daylight within the next two to three years. Standardization, spectrum policies and actual product development will follow after a few years. New innovations are needed to meet the goals of 6G, e.g., harnessing higher frequency bands, guaranteeing more secure communications and having more intelligent network management systems. In order to maintain Finland's leadership in mobile communications, there is need to develop 6G related IPR and educate hundreds of new 6G experts to support the Finnish industry. These goals can be met if large R&D projects can be launched. This in its turn means that significant funding for the projects should be guaranteed.

The document provides the starting point and guidelines for technology research and development to support the Finland's leadership in mobile communications and to create new innovations, not only in national but also in global scale. Boosting national telecommunication system and its verticals businesses, creating new business opportunities, and enabling the education of new talents and experts for ICT, are the key objectives also in coming years. The development of sustainable and secure communication platform together with support for emerging use cases will enable to fulfill the UN's sustainable development goals. Efficient communication and information exchange is one of the major requirements for future connected and networked society, requiring research and development actions for wireless connectivity, wired backbone networks, and enhancements and evolution of even Internet technologies and protocols. Also, software, software tools, and software-based architecture approaches, as being in central role also in today's communication and network system, needs to be studied and further developed to meet the requirements of future 6G system.

APPENDIX

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