FRAUNHOFER-GESELLSCHAFT ZUR FÖRDERUNG DER ANGEWANDTEN FORSCHUNG E.V.

ON THE ROAD TO 6G: DRIVERS, CHALLENGES AND ENABLING TECHNOLOGIES

A Fraunhofer 6G white paper

The work presented is part of the Fraunhofer lighthouse project 6G SENTINEL: Six-G Enablers: Flexible Networks, THz Technology and Integration, Non-Terrestrial Networks, SidElink, and Localization. Additional information on the status of the project is available at: www.iis.fraunhofer.de/6g-sentinel

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On the road to 6G

Deployment of 5G is still on its way while discussion about 6G technologies and corresponding research activities have started all over the world. Now is the time to work on the enabling technologies and fundamental building blocks of the new mobile communication standard and to join the worldwide discussion on use cases, functionalities and key-performance indicators (KPIs) of 6G. The large interest of academia and industry alike can be seen from the substantial amount of white papers and publications [2]-[13].

Standardization in 3GPP is just about to enter the second phase of 5G with 5G Advanced, starting from Release 18 beginning of 2022. 6G related activities are assumed to start around 2025, while first 6G deployments can be expected for 2030. The evolution of wireless mobile communication standards from 1G to 6G is depicted in Fig. 1. While 1G and 2G were focused on speech, data services and internet access were added in 3G. 4G brought the rise of the mobile internet whereas 5G is focusing on machine-to-machine communication and the internet of things. With 6G it is expected that humans and their needs will be in the center, once again (see section "New perspectives on 6G use cases").

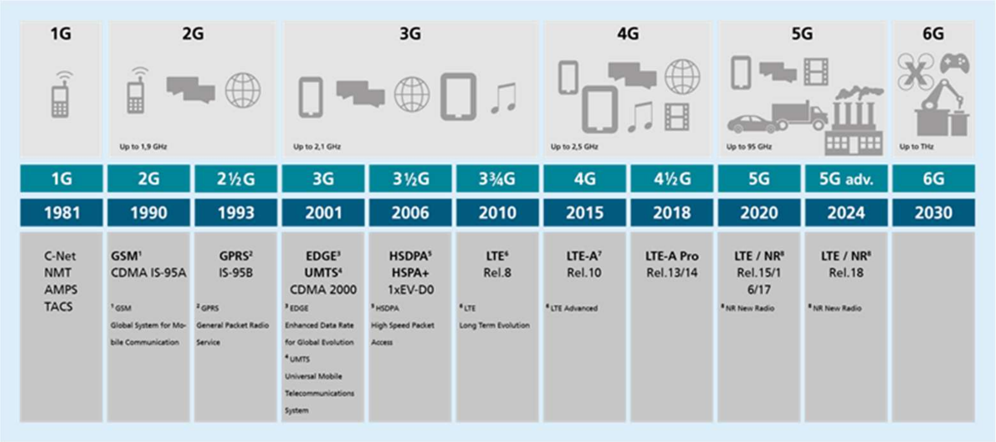

Fig. 1: Evolution of wireless mobile communication standards

An important trend in 6G is the convergence of the physical and the human world with the digital domain. Frequently discussed use cases for 6G are digital twins, virtual and augmented reality (XR), tele-presence, tele-operation and autonomous driving. To enable these use cases, a significant increase of 10x or more in the traditional KPIs like peak data rate, reliability, latency, connection density, and localization accuracy is required from 5G to 6G. On the technological side, the following enablers are crucial to achieve the required improvement in the KPIs:

- Terahertz radio technologies for ultra-high data rates
- Flexible networks for situationally-adapted network availability
- Fully integrated localization utilizing reinforcement learning for greater accuracy
- Optimized network architecture for best service quality and reliability

These enabling technologies are the foundation needed to respond to the challenges and requirements of 6G and, therefore, will have to be developed in a timely manner to be ready for integration as part of standardization as well as later products. If 6G technology can deliver its promises, it will stimulate and open new application fields and businesses.

Fig. 2 highlights the approach for bridging the gap between 5G and 6G with high innovation. Up to 2025, when standardization of 6G is expected to be ready to start, a very high potential for innovation is present in different domains and directions. In order to innovate in such a pre-standardization environment it is utmost important to consider the requirements of the network of 2030 and to break out of the specific 5G technology thinking. This step can be achieved only by conceptual development and practical feasibility assessments in a highly open ecosystem. Specifically, a new framework has to be considered where the basic assumptions of communications are highly different from 5G.

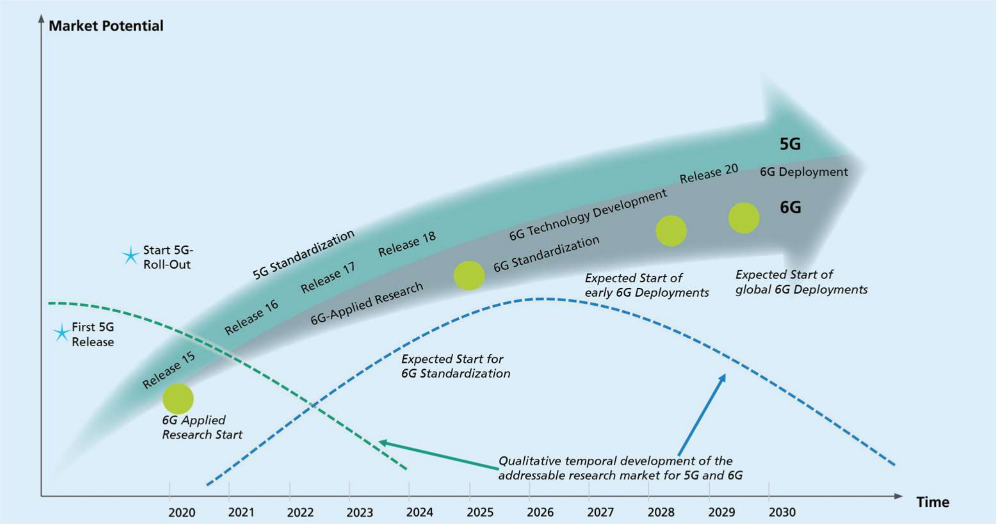

Fig. 2: Bridging the gap between 5G and 6G standardization with high innovation

An intense collaboration and exchange of concepts and designs between the different domains represents a way in which a coherent 6G network development can be accelerated. Only a holistic development including access, core, transport, devices and application domains could produce the expected results.

The Fraunhofer lighthouse project 6G SENTINEL [1] is addressing the specific technical challenges in these directions within a pragmatic, results oriented approach, aiming to boost the research activities, to prepare the standardization foreseen to start in 2025 and to accelerate the development and the foreseen adoption of commercial 6G networks in the year 2030.

What this white paper contains

- New perspectives on 6G use cases
- A high-level classification of challenges and requirements
- An approach and a roadmap for 6G R&D activities
- First steps towards a 6G architecture
- An applied research best-practice R&D roadmap
- The status and achievements of the 6G SENTINEL project

New perspectives on 6G use cases

While being still in an early phase regarding the potential use cases which will make 6G technology successful, due to the currently widening deployment of 5G networks, a set of highly potential directions could be identified for which the current standard commercial networks are not able to satisfy their requirements.

The classification of use cases presented here aims to entice the readers to change their perspective on how networks will transform. This does not exclude the further evolution of the 5G use cases which will happen in parallel, instead it potentiates it with a longer perspective addressing the communication needs of the year 2030.

Starting from the 4G Machine Type Communication (MTC) and 5G Ultra Reliable Low-Latency Communication (URLLC), a strong diversification of classes of services was observed beyond only increasing the network capacity, requiring specific network characteristics which could not be immediately fulfilled with the same infrastructure. While still expecting to serve more devices, using higher network capacity with more reliability or lower delay, the next generation of applications will require a mixture of these capabilities. For example, new enhanced Mobile Broadband Services (eMBB) such as Augmented Reality (AR) / eXtended Reality (XR) would also require a high level of reliability and a fairly low delay in addition to the network capacity. Similarly, the massive MTC would have to extend itself towards reliability and low delay to be able to handle fine-granular automatic environment management and to increase the network capacity when going in the direction of autonomous mobility and video-based insight generation.

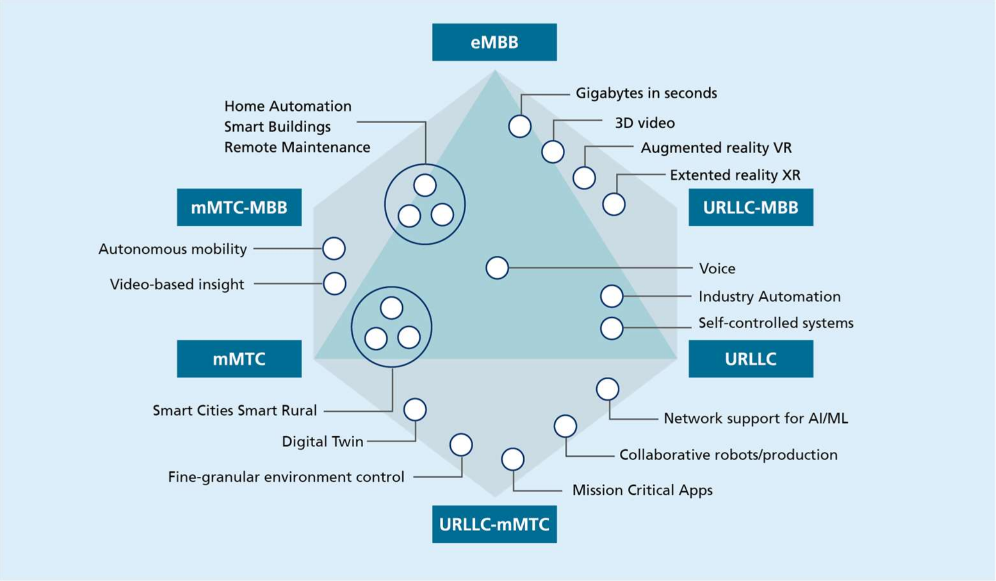

Fig. 3: Classification of 6G use cases

However, the key driver for 6G will remain the extended network capacity. And this can be achieved only through new, Terahertz (THz) spectrum-based technologies. Be it capacities of 4 Tbit/s for AR/XR, the under 100 µs delay for industrial or holographic presence, a 7-nines reliability, or < 1 cm-precision localization. For all of these use cases, no matter how much the compute capacity of the terminals will rise in the next years, an even higher compute capacity will be needed from the network. This continuous communication and the adoption of an increased number of devices will require a significant enhancement to the current 5G NR networks.

A key feature foreseen in 6G is the tight integration of localization in the network. Not only will position information be used for the end-user location services, this information can be exploited as well to improve the overall performance of the network, where early coarse information in one domain can be used to improve the other (e.g., coarse location information to enable beamforming with less feedback from the mobile device). Moreover, location information can be aggregated and, with the help of machine learning algorithms, used to coordinate the network. This gives rise to a "joint communication and positioning" concept.

With 5G, a first step was made towards the support of private and non-public networks. This opened the possibility to cover on-premise type of deployments resulting in more localized networks and in the option to develop full campus or even regional networks. However, this also opened the option to cover additional mobile use cases. For 6G, the next step is to be able to communicate with other on-premise locations, to establish larger scale networks or global networks, resulting in an ultra-flat deployment where the coverage is tethered to specific areas where the communication is needed (e.g., factory campuses around the world), integrated within a single network by using backhaul connections (similar to current large enterprise networks).

Another important aspect of 6G will be ubiquitous availability and to extend the coverage to reach a more global connectivity. 3GPP already started with the integration of satellites in the 5G system (called Non-Terrestrial Networks, NTN). This trend will continue with including and interconnecting multiple different satellite orbits and the network architecture will be evolved towards 6G, where also various airborne (UAVs, planes, HAPs) and spaceborne platforms (different types of satellites) will be interconnected with the terrestrial 6G network on a multi-layer (3D) architecture, requiring a dynamic, flexible RAN and core network architecture.

This range of new small networks span from fixed deployments such as currently foreseen for factory shop floors, temporary networks with additional base stations, increasing the local capacity, nomadic deployments, providing coverage for a given interval within a location such as a music festival or construction site, up to mobile deployments as needed by Public Protection and Disaster Relief (PPDR), public transport, logistics and maritime.

The envisioned future network flexibility along with the contrastive requirements of 6G services and applications presuppose a complex interplay between large-scale ecosystems of software and hardware network components, rendering classical theoretical approaches unable to seamlessly scale to the massive problem size. Artificial intelligence can alleviate this problem by being a key enabler towards self-adapting, data-driven and scalable orchestration of heterogeneous network services, resources and applications.

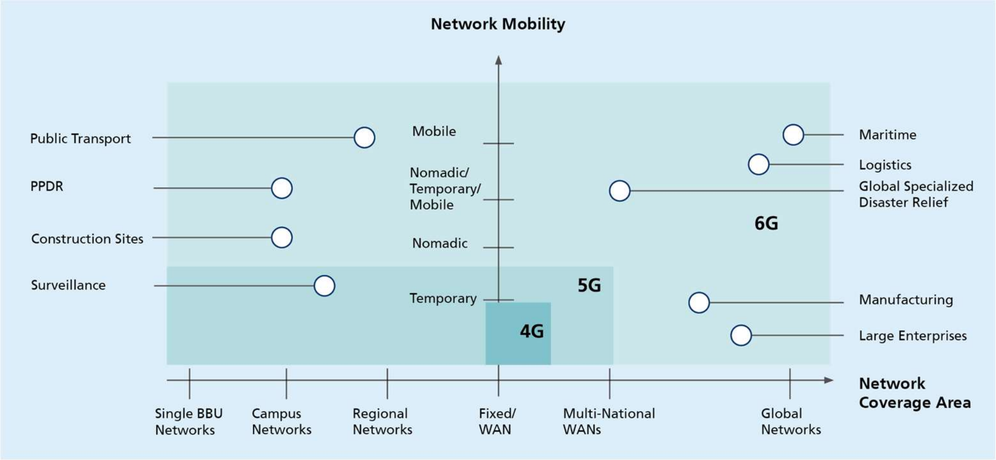

Fig. 4: 6G network deployments

Challenges and enabling technologies

Like previous generations, 6G is promising to fundamentally change how the consumers and businesses communicate, paving the way for a next generation of use cases able to capitalize on the speed, capacity, latency, and flexibility it offers as well as on the parallel compute, visualization, and artificial intelligence developments. It is expected that only a mix of heterogeneous technologies integrated within a comprehensive system can properly respond to the requirements.

A first summary of these technologies is presented here aiming to target the research in the expected direction.

Table 1: 6G requirements and enabling technologies

Technical Challenge	Requirements	Enabling Technologies
Higher Data Rates	Cover additional, higher frequencies (mmW, THz)	Decreasing the reception range, physical impairments, smaller cells
	Schedule available resources	Granular cell-free resource scheduling
Ubiquitous Availability	Larger Cell Size	Converging satellite and airborne
	Smaller nomadic cells	Dynamic spectrum allocation Support for split core networks Integrated backhaul management
Advanced cognitive insight	Positioning and sensing	Tight integration of sensing, positioning, and AI
	Fluid data exchanges	Secure data acquisition and exchange Data storage and curation
	Integration of AI in network management	Automatic, self-learning end-to-end decision chains for robust performance and security management.
	Integrated RAN management	Integrating RAN and core mobility management and QoS
Robust communication	Flexible, organically adapted core network functionality	Using software-only paradigms to design the core network service
	End-to-end coherent service delivery	Integrating backhaul technologies as part of the core network
	Ultra-reliable core services	Redesigning the core network for native reliability
	Clear split of state information and stateless components	Adapted mechanisms for state sharing and state migration
Heterogeneous infrastructure owners	Security and trust	Redefinition of the interaction between infrastructure and services
	Deterministic QoS	Extending backhauls with deterministic capabilities

	Multi-governance	Coherent system governance in multi-administrated environments
Sustainability	Requires reduction of carbon footprint of mobile networks	Network and UE energy reduction and power optimization
	Ultra-adaptable networks	Reducing the network overhead by very fast resource allocation and adaptation decisions.
Ultra-precise positioning	Finer temporal resolution	Higher frequencies (THz) allows the usage of signals with large enough bandwidth to provide the temporal resolution
	Finer angular resolution	THz signals enable ultra-massive MIMO antenna configurations which provide a very-fine angular resolution
Support for very large number of devices	Denser networks	Distributed and cell-free massive MIMO networks

In the following, a brief introduction to three important technological enablers, namely Terahertz technologies, flexible networks and integrated localization along with the associated research challenges will be given. The fourth research area, 6G network architecture, will be discussed in greater detail in the next section “Towards a 6G network architecture”.

Terahertz technologies for ultra-high data rates

To achieve the envisioned data rates of up to several Tbit/s in wireless links, bandwidths of 10 GHz and more are required. This can only be achieved at frequencies above 100 GHz, commonly referred to as Terahertz. The transmission channel for frequencies beyond 100 GHz, especially for indoor environments and sidelink communication between vehicles in the presence of mobility, is not sufficiently researched and new channel models need to be developed. Furthermore, the high frequencies increase the Doppler-rate while the large bandwidth leads to hardware impairments like phase noise and non-linearities that all need to be compensated. Novel approaches for integrated THz-transmitters with sufficient transmit-power like, e.g., a combination of GaAs and GaN or photonic InP technologies need to be investigated. In addition, cost efficient packaging technologies are required to decrease the cost of THz-modules. ([14], [15])

Flexible networks for unlimited 6G availability

The combination of the demand for heterogeneous infrastructure and ubiquitous coverage requires a flexible network with tight integration of a Non-Terrestrial Network subsystem.

In 6G, a more seamless integration of the different network nodes is expected than in 5G, where only the first steps for integrating of new non-terrestrial elements is standardized. With this level of integration, a truly global connectivity can be realized. Generally, three different layers of network elements (in terms of altitude) can be assumed: Ground-based platforms, airborne platforms, and spaceborne platforms. The complexity of the network will introduce different challenges, which need to be analyzed and solved to be able to deploy such 6G systems. On the system level, it is necessary to be able to add and remove new network nodes on a dynamic basis (e.g., LEO satellites, UAVs). Also, the inter-satellite routing between all these platforms will be a challenge. The delay between the platforms introduced by their motion will vary and the need for an accurate position of all elements is mandatory for proper resource and interference management in coexistence and spectrum sharing scenarios with terrestrial and non-terrestrial nodes.

Starting from the 5G core network, innovative concepts in the directions of secure end-to-end communication, trust in the infrastructure, reliable and deterministic backhauls, subscriber state distribution and data layer need to be developed. These features come to complete the 5G architecture and provide a basis for the 6G one towards a smooth end-to-end software network deployment on distributed network infrastructures.

Fully integrated localization in 6G networks for greater accuracy

Positioning in 6G networks is mainly driven by three technology enablers, namely distributed massive MIMO, jointly-processed coordinated multipoint transmission and ultra-dense networks which form the basis of cell-free massive MIMO systems. Cell-free massive MIMO does not entail a fixed network, but dynamically-changing clusters of access points that follow the user. With this paradigm shift, new opportunities and challenges rise. Fixed base stations that could be used as anchors for positioning are now dynamically changing. New fitting procedures, protocols, and functions need to be developed. Along with the tighter integration of localization in 6G networks comes also higher signaling overhead for the measurement of positioning-related signals. Novel approaches for a common reference signal for communication and positioning are required. Terahertz signals with very-large bandwidth and ultra-dense networks offer the possibility of ultra-precise positioning (in comparison, cm-precision localization is feasible with millimeter-wave signals [16]). Research on suitable ultra-massive MIMO antenna arrays, their characteristics and their impact on positioning performance is needed. Furthermore, AI methods, especially reinforcement learning (RL) for beam-management, are promising approaches for performance optimization. Owing their plug-and-play nature, RL-based methods are able to solve complex dynamical problems with quality-of-service and safety constraints without the need of hard-to-obtain models of the system. Moreover, they offer the possibility to extract interpretable decision rules [17].

Towards a 6G network architecture

A 6G architecture must consider how to support the selected use cases within the infrastructure context of 2030 when large amounts of compute resources would be available at different locations spanning from mobile phones, campus network back-ends, satellite payloads or on-demand in different mobile vehicles. For this, the network will have to morph to the existing compute and networking resources and to migrate specific subscriber contexts [2], [3].

Fundamental trends for the network of 2030

- a continuous decrease in compute costs and increase in capabilities enabling the virtualization of even more components
- a further increase in the software development paradigms enabling a 10-times faster software development
- extreme increase of the access and backhaul radio capabilities resulting in a significant larger set of options to be deployed
- large scale deployment of low orbit satellite networks, changing the perspective on global networks with ubiquitous availability

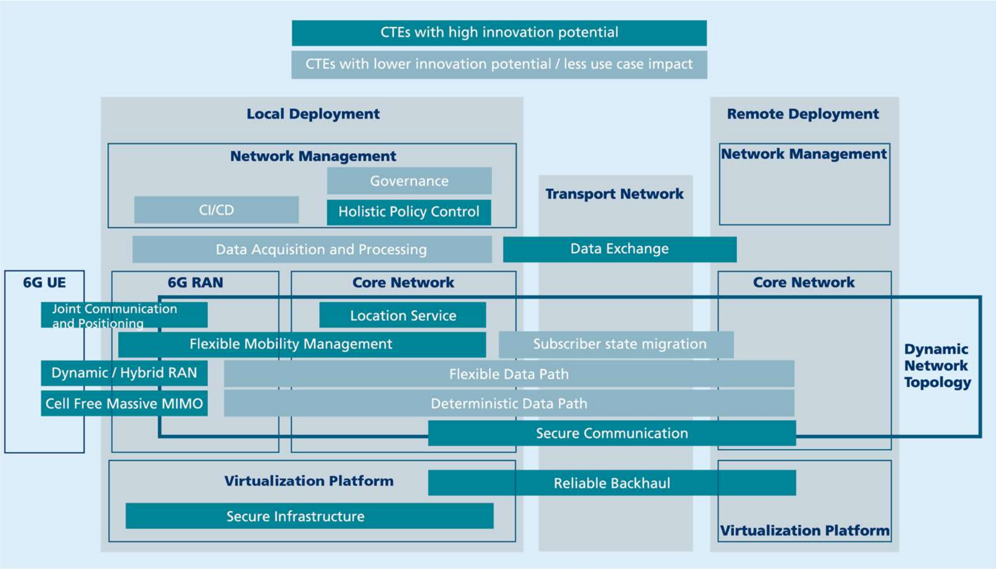

Fig. 5: Flexible networks high level functionality

Furthermore, it must include the current 5G functionality supporting the connectivity service such as authentication and authorization, connection and mobility management or session management. To be able to respond to the services' diversification, the architecture must maintain an openness to add new services in the form of new network functions. Albeit the 5G architecture aimed at this functionality with the adoption of a Service Based Architecture (SBA), such an open architecture is not possible as the new services are highly dependent on the offering of the existing ones. Ultimately, any extension requires the upgrading of existing services too, which leads to an extensive standardization process.

Table 2: Requirements and challenges of 6G network architecture

Requirements	Challenges
Infrastructure-free implementation	▪ Deployment on any hardware ▪ Transparent network bindings ▪ Account for noticeable service characteristics
Complexity reduction	▪ Re-grouping of functionality in new elements ▪ Remove functionality replicas ▪ Reduce the number of exchanged messages per procedure ▪ Uniform support of RAN and Core control in the edge ▪ Service Based Architecture to the UE
Organic growth	▪ Regrouping of the functionality ▪ Split processing and state elements
Simplify the addition of new functionality	▪ Reduce functional dependencies ▪ Reduce the number of interfaces
Very fast scaling	▪ Native support for load balancing ▪ Effective state sharing
High parallelization capacity	▪ Easy to split load across multiple worker entities ▪ Able to parallelize across distributed infrastructures
Continuous integration / Continuous deployment	▪ Graceful deployment of functionality during the runtime of the system – on ground, in the air, in the sky
Network management simplification	▪ Same type of components, uniform policies for scaling, uniform configurations, easy to adapt to automation
Support the existing 5G functionality	▪ Access control, authentication, and authorization ▪ Connection management ▪ Mobility management ▪ Session management ▪ RAN capabilities management ▪ Data path forwarding ▪ Lawful interception and charging

To be able to address these requirements in a graceful manner the overall architecture must be re-thought in the context of the parallel software engineering developments. This would presume to analyze from a conceptual level the concept of network functions.

As the name says, network functions are functionally defined based on their input and output interfaces, the transfer function which processes the messages and the subscriber state enabling the appropriate processing. Ultimately, a network function is a system by itself which works independently of the other network functions. As they have standardized input and output interfaces, they can be implemented and tested in isolation from other network functions enabling easy interoperability tests.

However, the complete independence of each network function is introducing many limitations. Maintaining independent state in each of the components is creating an information multiplication as well as it requires many messages to be exchanged between the components. Furthermore, the large number of messages create additional bindings between components, so instead of a highly flexible system we in fact have a very monolithic one with no possibility to deploy new services without cascading modification effects through the system.

Fraunhofer lighthouse project 6G SENTINEL

Based on the key drivers, challenges and enabling technologies identified before, new answers are needed to master the rapidly increasing performance requirements. 6G SENTINEL aims not only to push existing 5G technologies further, but also to develop brand new approaches that will help applications such as virtual reality, digital twins and autonomous driving achieve a genuine breakthrough with 6G.

In the Fraunhofer lighthouse project 6G SENTINEL (Six-G Enablers. Flexible Networks, THz Technology and Integration, Non-Terrestrial Networks, SidElink, and Localization), the five participating Fraunhofer Institutes are developing key technologies for the upcoming 6G mobile communications standard.

6G SENTINEL is addressing the most urgent challenges of mobile communications with practical routes to effective solutions (Fig. 6).

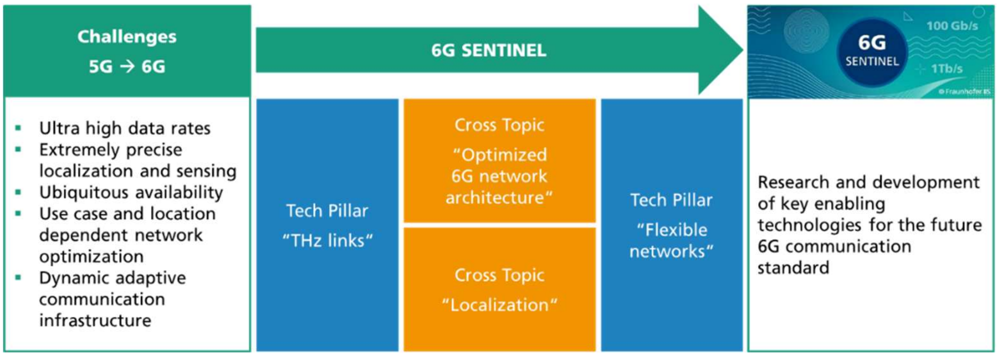

Fig. 6: 6G SENTINEL: challenges and enabling technologies from 5G to 6G

6G SENTINEL is targeting improvements to device antennas and front-end modules. It also seeks to optimize transmission technologies in the dynamic, heterogeneous deployments of the radio access network (RAN) and increase the flexibility of the core network. This means the project will support further developments of all relevant components of a mobile communications network.

The Fraunhofer institutes bring to the project complementary expertise from the fields of terrestrial and satellite radio access networks, localization, core networks, semiconductor technologies for THz communication and electronics packaging. This creates a unique conjunction of application know-how, technology expertise for individual aspects of a 6G network and overall systems expertise.

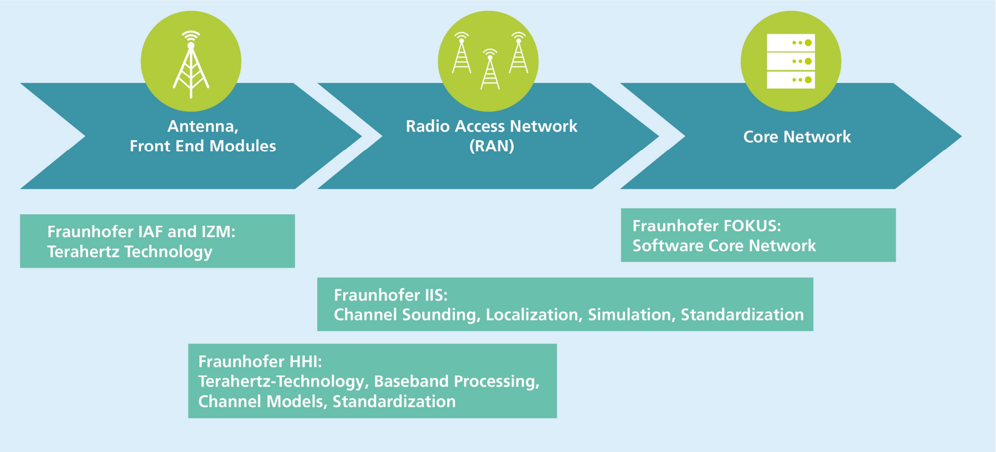

Fig. 7: 6G SENTINEL: technology expertise for 6G

6G SENTINEL follows a very pragmatic and agile approach towards technology development stemming from the large experience in working together with the industry and within standardization from Fraunhofer. Alongside, 6G SENTINEL aims to provide a first robust perspective on how 6G will evolve as well as to act as a lighthouse to the practical 6G developments. A very agile roadmap was put in place with significant results during 2021 and 2022 in terms of conceptual developments and a first demonstration of the new developments in September 2022. With this, 6G SENTINEL is acting as pioneering R&D within the applied research community.

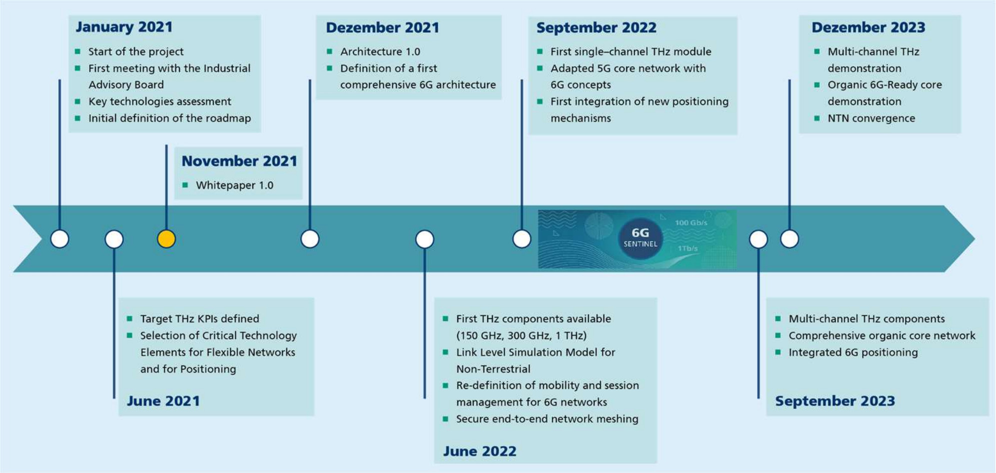

Fig. 8: 6G SENTINEL roadmap and milestones

What 6G SENTINEL provides

- Independent assessment of the 6G worldwide developments
- Design and specification of functionality addressing the foreseen infrastructure of 2030
- Integrated developments across heterogeneous technologies by world-recognized specialists
- Pragmatic technology development in the following areas:
    - THz communications
    - flexible networks
- Practical demonstrations of the technologies, showcasing how technologies work beyond only concepts and use cases lists
- Open environment to exchange ideas and to enable a common development of 6G
- Acceleration of the 6G environment development through supplying a comprehensive environment in which own research can be embedded

Further reading

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