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A secure and resilient 6G architecture vision of the German flagship project 6G-ANNA

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ABSTRACT The 6th generation of wireless mobile networks is emerging as a paradigm shifting successor to unifying the experience across the physical, digital, and human worlds, pushing boundaries on performance in capacity, throughput, latency, scalability, flexibility, and reliability, while prominently addressing new major factors, including sustainability, security and privacy, as well as digital inclusion. Many research institutions and initiatives worldwide have started investigations to make 6G a reality by approximately 2030. In Germany, federal funding from the German Ministry of Education and Research (BMBF) supports a large-scale 6G initiative, with its lighthouse project, called 6G-ANNA. The core aim of this project is to develop the key aspects of a holistic, sustainable, secure, and resilient 6G system design that will simplify and improve the interaction between humans, digital assets, and the physical environment. This paper shares the vision of the project's main technical working areas and advances, spanning topics from radio access, integration of multiple networks, as well as automation and simplification in networking to new applications and testbed scenarios, including real-time digital twins and extended reality. The industrial impact and relevance of standardization makes 6G-ANNA uniquely positioned to lead and realize the vision of next-generation wireless mobile network technologies, systems, and applications.

INDEX TERMS 6G, communications systems, wireless communications, network architecture, resiliency, security

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I. INTRODUCTION

As the 5G-Advanced [1] specification is coming of age for broadband cellular networks, 6G is emerging as a paradigm shifting successor to unifying the experience across physical, digital, and human worlds [2], beyond 5G richest capabilities of, "*connectivity and enabling a wider set of advanced use cases for verticals*" [3]. 6G leads to providing more intelligent services, better control, and new experiences to augmented humans. It is enabled by the following key enhancements including extended reality (XR), accurate positioning, resilient timing, and network operation efficiency (including energy efficiency and simplification) with rollouts expected in many markets. In addition to the enhancements offered by 5G, 6G design is also motivated by the key principles of traditional performance indicators (KPIs), that is, capacity, throughput, latency, scalability, flexibility, and reliability, as well as three key value indicators (KVIs): sustainability, security & privacy, and digital inclusion.

These KVIs not only drive the vision towards 6G architecture, but also present central challenges that 6G is envisioned to solve:

Sustainability is a major design criterion for 6G and needs to be considered from two perspectives: making networks more energy efficient and carbon neutral ("footprint") and enabling other businesses to provide solutions addressing the sustainability goals set by the United Nations [4] (we refer to it as the network's "handprint"). To this end, every aspect of the network's operation needs to be designed to minimize energy consumption, resulting in more sustainable water use (e.g., for cooling systems in data centers) and reduced carbon emissions. Additional improvements in device power savings, efficient radio transmission, and simplification of the network architecture are expected to further reduce the energy footprint despite the ever-growing traffic demand.

Second, improving **security and privacy** to better safeguard communication systems and personal data continues to be a major goal. Various networking scenarios, including private campus networks and a novel network of networks (see Section III.B), present new challenges and opportunities to implement both security and privacy *by design*.

Finally, **bridging the digital divide** (aka digital inclusion) is a key goal of 6G. Enhanced connectivity on a global scale will allow access to healthcare, education, and greater economic opportunities for all humans. To this end, 6G must provide connectivity everywhere with good network quality and affordable costs.

The remainder of this paper is organized as follows. This section provides an overview of the current global 6G ecosystem by listing key 6G initiatives globally and positions 6G-ANNA within this ecosystem. This is followed by an outlook to 6G standardization efforts. Section II presents the use cases and requirements that 6G-ANNA derives for 6G. Section III details the envisioned research directions and the proposed architecture. Finally, Section IV describes the planned evaluations and proof-of-concepts.

A. CURRENT GLOBAL 6G ECOSYSTEM

Many research institutions and initiatives worldwide have started investigations to make 6G a reality by approximately 2030. Significant efforts towards this end are underway in the US, Europe, and China. In particular, the German Ministry of Education and Research (BMBF) funded a large-scale initiative, including the 6G lighthouse project, called *6G-ANNA*[1]. The project is a consortium of 30 partners from industry, small and medium enterprises (SME), research institutions, and universities based in Germany. The project focuses on developing a blueprint for a functional 6G end-to-end system architecture designed for energy efficiency ("footprint"), security, and resiliency, which supports a variety of use cases, as detailed in Section II. The 6G-ANNA technical working areas span topics such as radio access, integration and interaction of multiple networks, automation and simplification in networking, including digital twins and extended reality. Several planned testbeds and proof of concepts (PoCs) will demonstrate the key findings of the project.

The *6G Platform Germany*[2] aims to make scientific contributions to the content design of 6G and ensure the scientific organizational support of the processes necessary for the successful implementation of the German 6G program. It is home to four 6G research hubs in Germany, namely 6G RIC, 6GEM, 6Glife, and Open6GHub, which combine the know-how from universities and research institutions. Additionally, the 6G Platform is the interface between these hubs, 18 6G industry projects, including 6G-ANNA, 7 resilience projects, and the optical networking project AI-NET.

Horizon 2020[3] and the European Smart Networks and Services Joint Undertaking (SNS JU)[4] set goals to ensure industrial leadership for Europe in 5G and 6G, pooling resources from the EU and industry towards 6G research and innovation. Hexa-X[5] and its successor Hexa-X-II[6] are two notable EU flagship 6G research projects with strong participation from cellular service providers (CSPs), major industries, SME, and academic partners. The foundation for an end-to-end 6G system architecture was laid by Hexa-X, and Hexa-X-II continued to define a blueprint and system validation of the sustainable, inclusive, and trustworthy 6G platform. The projects also aim to ensure technological readiness in critical areas and EU strategic autonomy.

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[1] 6G-ANNA: https://6g-anna.de/

[2] 6G Platform Germany: https://www.6g-platform.com/

[3] Horizon 2020: http://ec.europa.eu/programmes/horizon2020/en

[4] SNS JU: https://smart-networks.europa.eu/

[5] Hexa-X: https://hexa-x.eu/

[6] Hexa-X-II: https://hexa-x-ii.eu/

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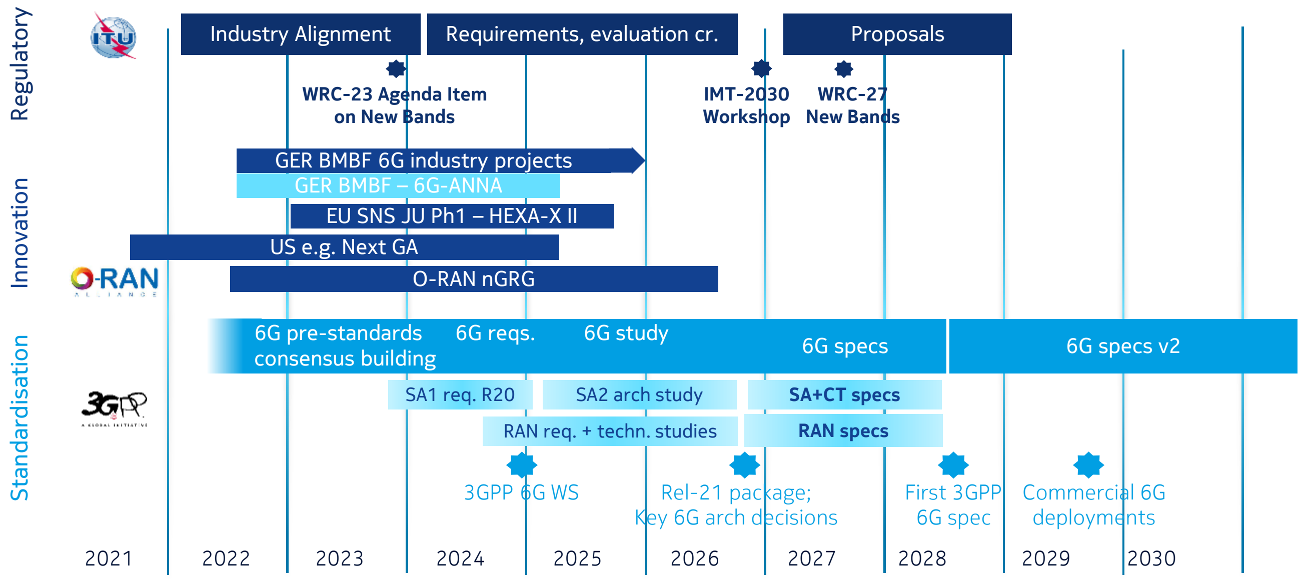

FIGURE 1. ***6G timeline highlighting main projects, phases and milestones along the road towards first commercial 6G deployments.***

In the US, the *Next G Alliance*[7] is an initiative to advance North American wireless technology leadership over the next decade with a strong emphasis on technology commercialization, including the 6G roadmap. Its working groups cover all aspects of spectrum, technology, applications, societal and economic needs, and green networking. Several whitepapers have already been released by related working groups[8].

Moreover, the *Resilient and Intelligent Next-Generation Systems (RINGS)*[9] program is a noteworthy US NSF-led initiative to accelerate collaborative academic research in areas with a potentially significant impact on next-generation networking and computing systems. It focuses on significantly improving the resilience of such networked systems.

China has also initiated several 6G activities, including the *IMT-2030 (6G) Promotion Group*[10] which has already published several deliverables on 6G vision and many technical 6G research areas, and the *6G Alliance of Network AI (6GANA)*[11] focusing on the exploration and promotion of 6G architectural innovation for network artificial intelligence (AI). The Beyond 5G Promotion Consortium (B5GPC, Japan)[12], 5G Forum (South Korea)[13], and TSDSI (India) [5] have begun investigations and research on 6G scenarios, requirements, 6G architecture design, and technological innovations.

Multiple aspects are common to most 6G initiatives today, including, but not limited to, spectrum aspects, 6G architecture and relevant technologies, and use cases and requirements.

B. 6G STANDARDIZATION EFFORTS

The earliest commercial and standard-compliant 6G deployments are expected to become available by late 2029 (Figure 1). The consortium 3GPP (3rd Generation Partnership Project)[14] is expected to be the key player in developing the main protocols for the 6G mobile telecommunications standard, while itself utilizing protocols developed by other organizations (e.g., IETF) and being extended by initiatives such as the O-RAN Alliance[15].

Standards organizations typically work following an 18 to 24 months release cycle, starting with an investigation of requirements derived from use cases and verticals markets (e.g., SA1 - Service and system Aspects working group 1 in 3GPP). Next, the services and architecture needed to support the agreed requirements are studied and specified at a functional level (e.g., 3GPP SA2), which is followed by detailed technical specifications (“Stage 3”). Examples of the latter are the 3GPP CT (Core network and Terminals) working groups.

To achieve the 2029/2030 deployment target, the first release of 6G standards needs to be made available by mid-2028 as Stage 3 specifications. To this end, 3GPP will start working on 6G requirements by the end of 2023. Technical studies are expected to take place in 2025 and 2026, and normative specification work is expected to start in the second half of 2026. It should be noted that also other (pre-)standards organizations are preparing for 6G, including the O-RAN Alliance currently investigating several research questions as part of a newly established next Generation Research Group

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[7] Next G Alliance: https://www.nextgalliance.org
[8] https://www.nextgalliance.org/6g-library/
[9] NSF RINGS: https://www.nsf.gov/pubs/2022/nsf22590/nsf22590.htm
[10] IMT-2030(6G) Promotion Group: https://www.imt2030.org.cn/
[11] 6G Alliance of Network AI (6GANA): https://www.6g-ana.com/
[12] Beyond 5G Promotion Consortium (B5GPC): https://b5g.jp/en/
[13] 5G Forum: http://www.5gforum.org/
[14] 3GPP: https://www.3gpp.org/
[15] O-RAN Alliance: https://www.o-ran.org/

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(nGRG). The results and findings from the different research organizations and 6G initiatives summarized above will play a critical role in the current ongoing 6G pre-standards consensus building. Simultaneously, regulatory aspects and industry alignment remain critically important, such as spectrum allocation for 6G. The latter will be discussed at upcoming world radio conferences (WRC), and ITU-R will move its 2030 vision into a set of IMT-2030 standards by around 2030.

II. 6G USE CASES AND REQUIREMENTS

Most previously described initiatives have already identified and published a set of 6G use cases [6][7][8]. The Hexa-X project [2] is worth noting in this context categorizing its use cases into six use case families: (i) enabling sustainability, (ii) hyperconnected resilient network infrastructures, (iii) trusted embedded networks, (iv) robots to cobots (collaborating robots), (v) telepresence, and (vi) massive twinning. In contrast, Next G Alliance divides its use cases into four groups: (i) network-enabled robotic and autonomous systems, (ii) multi-sensory extended reality, (iii) distributed sensing and communications, and (iv) personalized user experience [6]. The NGMN Alliance also applies four categories: (i) enhanced human communication, (ii) enhanced machine communication, (iii) enabling services, and (iv) network evolution [8]. Thereby, the last category, with energy efficiency, coverage expansion, and trusted native AI, does not actually describe use cases but rather focuses on goals for network evolution towards 6G.

Several of the abovementioned initiatives have also identified generic requirements for the described families of use cases. Consequently, many of these requirements have a quite large range of values. The 6G-ANNA project started to detail more concrete requirements for selected relevant use cases, as in most application areas, not all extreme requirements must be met at the same time. In addition, the 6G-ANNA project puts a specific emphasize on energy efficiency metrics and extends the requirements regarding interworking between networks and network generations. For example, in the 6G-ANNA, UEs can take up different roles, such as the host of a sub-network, member of split inference, or federated model training, with corresponding capabilities exposure, and necessary state synchronization. In addition, there is currently a lack of agreed proof-points for the KVIs, that is, how to demonstrate benefits and translate “key values” into measurable metrics.

6G-ANNA identified several areas that it uniquely addresses and extends in comparison to other activities. For instance, while many initiatives consider use cases that cover the mobility of people and cars, the aspects of trains and airplanes are still widely missing, whereas 6G-ANNA addresses these challenging environments. Furthermore, although the importance of security is highlighted in most 6G initiatives, specific use cases for security applications are few and far between. 6G-ANNA includes a use case entitled “*Critical 6G services for remote operators*” that demands connectivity with advanced security protection to guard against sophisticated malicious attacks. This is only one example of a security and privacy use case that the 6G-ANNA addresses.

6G-ANNA, with a primary focus on factory and industrial environments, as well as mobility aspects for vehicles (automotive, aerospace, etc.), studies use cases such as:

--“***Public safety networks***” enables highly robust emergency systems with specific communication requirements. In particular, the use case requires very high network availability and reliability, with a potentially high number of users (see Section III.A).

--“***Dynamic switching of control access to sub-networks and hosts***” includes a scenario in which hosts are connected to the *network of networks* (see Section III.B) dynamically changing their role from client to (sub-)network, and vice versa.

--“***Intelligent network operations and multi-X orchestration in 6G networks***” has a high level of robustness, reliability, and sustainability requirements, with several identified technology gaps (see Section III.C).

--“***Real-time digital twinning of factory environments***”, where a better control is needed of the factory environments including improvements in positioning, mapping, and semantic segmentation. From a technological point of view, real-time sensor retrieval and (dynamic split) processing and efficient real-time data reduction are some of the gaps to be addressed (see Section III.D).

--“***Massive multisensory merged reality***” offers a portal to a metaverse experience powered by XR and requires a broad range of KPIs as well as the privacy KVI (see Section III.A).

--“***Critical 6G services for remote operators***”, e.g., for vehicles demanding for connectivity with advanced security protection to guard against sophisticated malicious attacks (see Section III.F).

III. RESEARCH DIRECTIONS (in 6G-ANNA)

A. 6G ACCESS

1) SPECTRUM

The spectrum where the 6G cellular networks will be allowed to transmit imposes fundamental restrictions on: **(i)** how the 6G radio access network (RAN) can operate (e.g., regulatory restrictions in terms of radiated power and interference management mechanisms); **(ii)** what types of services can be supported (e.g., high-throughput applications can be supported with large bandwidths, which in turn are only available in specific, high spectrum bands); and **(iii)** what network performance can be achieved (e.g., carrier frequency and available bandwidth that determine the coverage, throughput, number of supported mobile devices, etc.). Therefore, it is crucial to consider the spectrum possibilities for the operation of 6G before proceeding with a detailed design of its RAN.

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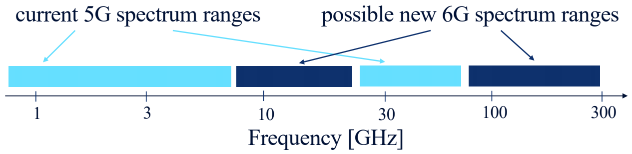

FIGURE 2. **Spectrum range for future 6G radio access, illustrating spectrum already available for 5G (cyan) and possible new spectrum for 6G (dark blue).**

We briefly review the spectrum in which 6G networks are expected to operate in the future. Figure 2 shows an overview of the spectrum ranges in which some bands can already be used by cellular technologies prior to 6G, as well as ranges where potential new spectrum bands could be opened for 6G. Overall, these spectrum ranges cover diverse regulatory access rights, such as licensed exclusive, unlicensed, and licensed nonexclusive. Regarding the spectrum that can already be used for mobile cellular services, we consider Germany as the region of focus for the 6G-ANNA project. This spectrum comprises broadly 700 MHz–3.7 GHz with exclusive (country-wide) licenses, and 3.7–3.8 GHz and mm-wave bands within 24.25–27.5 GHz with local licenses [9][10].

Regarding the new spectrum (i.e., the dark blue ranges in Figure 2), it is not yet clear at a global level whether this spectrum will actually be available for mobile communications. Overall, sub-THz bands are, in any case, suitable only for very specific use cases (e.g., high-definition merged reality in indoor environments), owing to the very high radio propagation attenuation, despite the very large bandwidth. By contrast, the range of 7–20 GHz is more promising for extending the bandwidth while ensuring sufficient coverage. However, incumbent services already exist within this range [11]. Thus, it is not yet clear whether and how many of these bands will be opened for 6G. Additionally, even if some are to be opened, strictly defined regulatory rules are expected to coexist with incumbent technologies and protect them from interference. The next ITU-R World Radio Conference (WRC-23) will discuss the identification of bands in the 6–10 GHz range and additional bands for international mobile telecommunications (IMT) services [11].

Given these considerations, 6G operation in existing licensed bands for cellular technologies is crucial because this spectrum is readily available for pre-6G 3GPP communication technologies, and it is straightforward to employ coordinated interference management techniques within the network of a single licensee. Nonetheless, it is important to ensure the coexistence of 4G/5G networks with the same licensee. Thus, migration solutions from 4G/5G to 6G should be carefully considered and are part of ongoing 6G-ANNA research. We note that such solutions were already developed and standardized by 3GPP for 4G and 5G technologies, that is, dynamic spectrum sharing (DSS) [12]. Consequently, future spectrum-sharing techniques between 5G and 6G can be based on lessons learned from DSS, which will also be explored in 6G-ANNA.

2) ADAPTIVE PHYSICAL LAYER

For 6G radio access, further evolution of the physical layer (PHY) is expected, fulfilling the broad requirement range of the previously mentioned 6G use cases, while operating in different frequency ranges and deployment scenarios. The 6G-ANNA project investigates the key technology enablers for making the PHY more adaptive. Furthermore, 6G-ANNA analyzes the benefits of the integration of AI in PHY and develops concepts for massive and distributed multiple-input multiple-output (MIMO) antenna systems.

Using a single PHY design to implement different 6G use cases is not optimal in terms of the operational cost and energy consumption. This is because of the various requirements and deployment scenarios that affect the channel characteristics, coverage, and traffic over time and area. For instance, conventional cellular networks exhibit non-uniform coverage and user distribution as well as varying data usage patterns throughout the day. This can be translated into different spectral efficiency (SE) requirements in time and space, based on actual data rate demands, available radio resources, channel status, and interference conditions.

Consequently, it is inefficient to concentrate the physical layer design on achieving a high SE, which is rarely used. Although adaptive modulation and coding schemes (MCS) and orthogonal frequency division multiplex (OFDM) numerologies, such as employed 5G PHY, provide a solution to configure the transmission parameters according to SE requirements, this approach does not consider the potential of utilizing other energy-efficient modulation schemes with optimized analogue hardware. Moreover, in linear modulations, analogue-digital converter (ADC) power consumption is expected to present an energy-consumption bottleneck for bandwidths beyond 300 MHz [13].

Therefore, the PHY adaptability needs to be extended to multiple modulation schemes with corresponding hardware (HW) options, and switching between them needs to be enabled based on the SE requirements of energy consumption. Such an approach has been denoted as the “Gearbox PHY” [14], where multiple options (gears) are optimized in terms of hardware and modulation for different SE ranges. For example, the lowest gear could employ pulse modulation, which is suitable for a low SE. The second gear operates with 1-bit ADCs and zero-crossing modulation (ZXM). The third gear can be designed with constant envelope modulation and a low-resolution ADC. The highest SE requirements can be supported by gears that employ linear modulation and MIMO schemes, etc. Changing the type of modulation requires the full switching of the transceiver chain. Additionally, within one gear, flexible adaptation of the design with traditional modulation and coding schemes can provide a fine-tuned SE.

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Accordingly, there are three emerging research areas: 1) baseband transceiver design considering adaptive modulation for individual gears; 2) underlying radio architecture considering frequency band, bandwidth, and hardware constraints; and 3) analysis of the conditions for switching the gears.

One of the further key aspects of 6G wireless systems is expected to be their "by-design" ability to learn and adapt to dynamic environments where artificial intelligence (AI) methods play the central role [15]. Computational learning agents have the potential to enable 6G wireless systems to cope with real-time changes in their environment, such as channel variation, signal strength, or interference, resulting in improved network performance.

AI concepts in the 6G PHY are expected to employ learning-based methods in the physical layer to replace or complement traditional transceiver functions, such as channel estimation (CE), synchronization, signal, and modulation detection. Alternatively, it can perform these tasks jointly in the system; for example, in joint estimation and detection [16].

A major obstacle to 6G-AI integration is the lack of transparency and dependability of AI algorithms. This opaque behavior and lack of model explainability hinder the widespread adoption of AI-empowered services in real systems. The 6G-ANNA project addresses the need to develop AI schemes that deliver the same level of dependability and clarity as classical model-based optimization algorithms [17].

3) DISTRIBUTED/MASSIVE MIMO

Massive MIMO has been one of the main technological innovations for 5G RAN because of its potential to achieve dramatic spectral, energy, and hardware efficiency gains at a relatively low cost and complexity [18][19]. However, considerable research effort is still needed to bring massive MIMO technology to maturity and to develop commercially attractive solutions that can deliver the full promised gains in practical scenarios [20]. Of particular interest is its extension to distributed MIMO deployments and its implementation via virtualization and cloudification concepts that enable flexible “cell-free” operations offering more uniform coverage and quality of service [21][22][23]. In this context, a key research challenge is the design of PHY algorithms and deployment architectures with scalable fronthaul overhead and computational complexity. The development of satisfactory solutions is currently prevented by the limited theoretical understanding of nonideal distributed MIMO systems. For instance, the long-lasting open problem of optimally distributed precoding/combining under limited channel state information sharing [23][24] was solved only recently in [25] using the theory of decentralized decision making. We believe that future research on distributed MIMO systems should focus on fundamental questions, such as “which task should be performed where, and on the basis of which information?”. Promising approaches covered in 6G-ANNA may include analytics tools, as in [25][26], or decentralized learning methods, as in [27].

The trend in 5G and 5G Advanced massive MIMO is to increase the number of base station antennas while limiting the antenna area, as well as to enable site reuse and deployment of compact antenna systems. However, increasing the physical size of the base station antenna arrays is also beneficial, as it increases the spatial resolvability (i.e., the possibility of targeting specific UEs) of the array and changes the nature of the propagation channel by increasing the probability of line-of-sight between users and antennas, both of which can be used to increase the spectrum and energy efficiency. While spatial multiplexing and distributed computation techniques from massive MIMO and distributed MIMO can be applied to very large aperture massive antenna arrays, further reductions in complexity and spectrum efficiency gains can be obtained by new, low-complexity techniques tailored to very large arrays to help bring to practice the potential gains from such arrays.

4) RAN PROTOCOLS & RADIO RESOURCE MANAGEMENT (RRM)

Further research topics within the scope of 6G-ANNA are the 6G RAN protocols and architecture for user and control planes, including mobility, as well as radio resource management (RRM). The overall objective is to simplify the protocol stack, resulting in lower operating costs while maintaining flexibility for optimally handling the diverse and demanding QoS requirements for 6G use cases. In particular, Link Layer (OSI layer 2) aspects in the area of uplink scheduling, latency reduction, retransmission schemes, re-ordering of packets, air-interface security, and QoS are expected to help achieve significant improvements compared with 5G.

6G networks introduce a new architectural challenge and requirement, that is, the integration of sub-networks, such as with flexible duplex schemes and the related architecture and system modifications in RAN protocols. Owing to this so-called *densification*, managing the radio resources in sub-networks becomes more critical. In addition to the spectrum issues that must be considered, mobility within the network adds another level of complexity to RRM. Higher mobility leads to higher Doppler spreads, causing spectral broadening, and lower coherence times, which consequently complicate the actual channel estimation. Because of mobility, the interference pattern changes over time, and considering some of the 6G services with stricter latency requirements, it is anticipated that the typical reactive approaches applied in 5G for interference and RRM might need to be enhanced by proactive components [28][29]. To cater to the diverse requirements of these time-critical services, the interference management must be proactive. To this end, 6G networks should be able to predict the demand and availability of radio resources that are determining the current spectrum usage in terms of time, frequency, and location.

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One way to achieve this is through the integration of native and distributed AI/ML approaches as an add-on to existing signal-processing algorithms. This includes aspects of interference estimations/management, parameter optimization, and access schemes for energy efficiency, security, resilience, and mobility. Together with the 6G Network of Networks design principles that enable further decomposition of the network into individual sub-networks, the resilience of distributed AI/ML approaches in terms of reliability and RRM needs to be further analyzed to investigate the impact of decomposition on their overall performance [30].

5) CLOUD-BASED RAN ARCHITECTURE

Research on the 6G RAN architecture design has three aspects: 1) the functional modules and their connecting interfaces as defined by the standard, 2) the resulting potential implementation modularization (vendor-specific choice, e.g., based on hardware platforms and technologies), and 3) the resulting potential deployment options (typically according to operator-specific needs). The functional architecture should thereby allow for implementation and deployment choices to make best use of available RAN resources, available hardware, and technologies, as well as to best serve in the required deployment scenarios. One key technology candidate to be considered for flexible implementations is the cloud-based architecture, that is, one based on a virtualized network function (VNF), which is seen as an integral part in the design of the 6G RAN.

In the envisioned 6G market, a mixture of communication service providers (CSPs), webscalers, and enterprises in shared networks is expected, with the need for security, isolation of services and service automation, and the requirement of the use of generic processing platforms in addition to vendor-specific solutions, by SW-based solutions and HW accelerator pools. All of these are enabled by the cloud-based RAN approach, and furthermore, would enable RAN as-a-service solutions for pay as you grow opportunity.

6G-ANNA proposes to analyze the functional decomposition and placement options in cloud-based implementations and the impact on performance metrics such as energy consumption, throughput, latency, reliability, and security.

Furthermore, in 6G networks, a higher variance in the QoS requirements is expected. Therefore, improvements to the concept of network slicing will be investigated in this project, for example, slices or service types as a combination of network slices with VNF dimensioning and dynamic scaling with AI-based workload models and traffic prediction. This more flexible placement of VNFs per slice or service type may enable higher pooling gains and energy efficiency while meeting the service requirements. For example, it would enable guarantees for certain services that require high robustness, such as those needed for public safety networks.

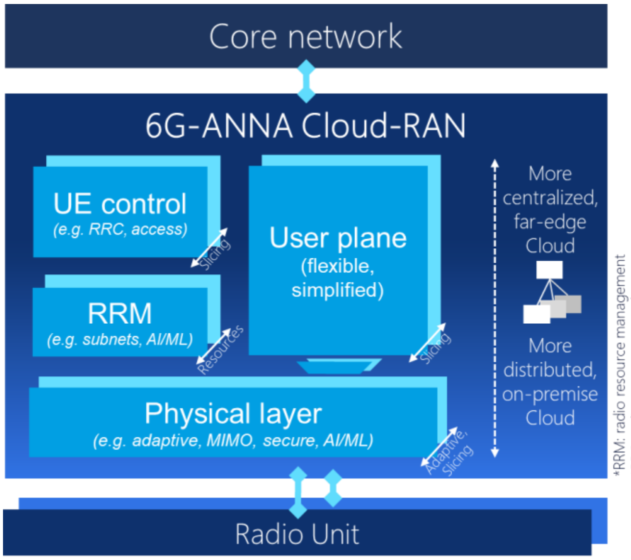

FIGURE 31. **6G-ANNA cloud-RAN components.**

Figure 3 illustrates the 6G cloud-RAN technology components investigated in this project. Flexible function placement is therein possible in more centralized/far-edge cloud implementations or more distributed on-premise cloud environments, particularly for slice-specific components. In this way, it allows balancing between scalability gains achievable with centralized processing and latency gains achievable with distributed processing close to the radio interface. Slicing may be applied to functions such as UE-control, including radio resource control (RRC), and further functions such as access control/management, as well as to the user plane protocol stack, for which modularization and simplification compared with 5G is expected. This decomposition into slices or service types may include the functionality of both a 5G-defined centralized unit (CU) and a distributed unit (DU). Radio resource management (RRM), including scheduling for the network and sub-networks, including potential enhancements by AI, may be instantiated per radio resource group, such as multiple cells or carriers. The physical layer, where project focus lies on MIMO enhancements, security, and AI integration, may also be sliced and different instances may be created as per "gear" as described above. The Cloud-RAN interfaces with the core network and multiple radio units.

B. NETWORK OF NETWORKS (NON)

In our context, a network refers to a group of interconnected hardware devices and software components that can communicate with each other and share data, resources, and services. Hardware components refer to conventional computing and communication devices such as computers, servers, routers, switches, and base stations. In comparison, software components can be digital twins of hardware devices for monitoring, control, and optimization purposes. Various individual networks include purpose-built technologies that

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cause deployment, interoperation, and scaling issues. Therefore, developing protocols and standardization for tightly integrated networks is crucial, which in 6G-ANNA is referred to as *network of networks* (NoN).

1) 6G-ANNA NETWORK OF NETWORKS (NoN)

A NoN is a compound of different networks and services that enable the efficient usage of network resources. In this section, the envisioned architecture and environment for sub-networks -a part of the NoN architecture- are described along with their desired key characteristics. The architectural classification of sub-networks, envisioned management functions, interworking, physical access, and mobility aspects are explained.

As shown in Figure 4, a network within a NoN can comprise of one or several networks (here shown in layers), may peer with networks on the same layer, may lay on top of "lower layer" networks, and must offer access to higher layer networks or hosts. A host is the data endpoint or user and connects to a network. In most cases, the host is separated from the network, while in some cases, as in the context of sub-networks, it is a part of the network. By allowing other hosts to attach, it may also turn into a network and vice versa. Figure 4 depicts two example networks: network 1, which is an operator network, and network 2, which is an edge-sub-network. The two networks interact via well-defined interfaces.

2) 6G SUB-NETWORKS

As part of the NoN concept, 6G-ANNA defines the concept of *6G sub-networks* providing spatially limited means of communication with extreme demands in terms of bandwidth, latency, reliability, and availability. As the name sub-network suggests, it is integrated and managed by a (public or private) operator network (ON). Access to the ON and the associated sub-network devices (SN-UEs) is provided in a bidirectional manner. This means that a sub-network provides both uplinks and downlinks to an ON and can serve as a relay to another sub-network, as illustrated in Figure 4. In the context of a Network of Networks (NoN), 6G sub-networks are a possible manifestation of a specialized network that integrates into the NoN to allow for an end-to-end design of a 6G system.

It should be noted that in 6G-ANNA we envision sub-networking to be different from a traditional cellular approach using base stations with a limited range (e.g., pico/femto cells). Although sub-networks also allow uplink communication of the associated devices to an ON through a gateway instance as part of a sub-network controller (SNC), the main goal of sub-networking is to enable 6G-based communication within the sub-network or devices belonging to different sub-networks in the local vicinity. Furthermore, specialized services (e.g., computing capabilities) are provided within the sub-network. Because of the spatially limited transmission range and tailored protocol stacks in the gateway, low-energy devices are suitable for sub-networking, which is critical for future networks. For example, wearable electronics for augmented reality rely on low power consumption and require high data throughput and low latencies. Other use cases investigated in 6G-ANNA include public safety, industrial automation, and mobility in vehicular and aeronautical environments. In Figure 5, two local automotive sub-networks exist that allow wireless sensor data transmission, which requires extreme data rates and reliability. In this way, traditional wired connections may be supplemented or even replaced by 6G local communication, increasing system reliability through redundancy, reducing wiring costs, and optimizing the weight of the communication system (and thus the overall weight of the vehicle itself).

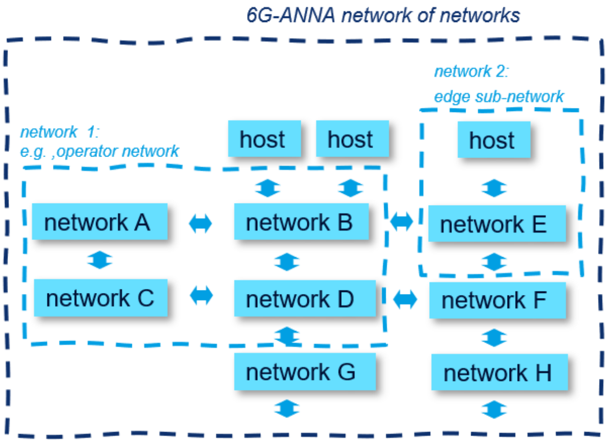

FIGURE 4 **6G-ANNA network of networks is a compound of different networks and services enabling an efficient usage of the network resources.**

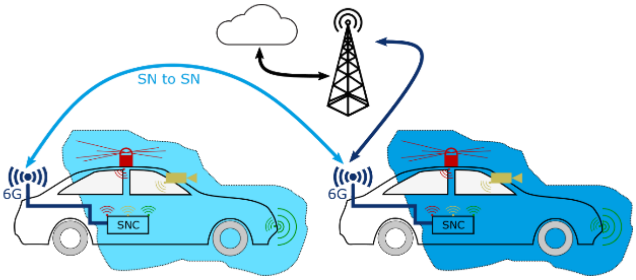

FIGURE 5. **Two in-car sub-networks with wireless sensor communication. Furthermore, 6G ON uplink and inter-sub-network connectivity is provided.**

As indicated before, in 6G-ANNA, sub-networks are regarded as edge networks, implying a typically small spatial distance of the connected UEs. From an architectural point of view, sub-networks are a hybrid solution that combines features from private networks and local sidelink-based communication. Sub-networks are envisioned to include tens to hundreds of devices with communication being more locally contained, whereas private 5G or 6G based campus networks typically encompass thousands of devices and traffic stretches across many different (control) networks. In addition, sub-networks are typically under different ownership. Furthermore, sub-networks can operate autonomously without the availability of an ON for a limited

TABLE I
COMPARISON OF DIFFERENT NETWORK CLASSES

	Public Network	Campus Network	Sub-Network	Sidelink
Dimension	Country/Region	Building / Company site	<~100 m	<~100 m
Number of Nodes	Millions	Thousands	Hundreds	Two
Spectrum	Licensed	Licensed	Licensed/Unlicensed	Licensed/Unlicensed
Autonomy from ON	-	Depends on deployment	Configurable	Mode 1/3: no Mode 2/4: yes
Access	3GPP	3GPP	3GPP, non-3GPP wired/wireless	3GPP

time, allowing the sub-network to continue providing its services, while some features might be limited by sub-network capabilities. An overview of the different network types is presented in Table 1 [31][32].

The management and orchestration of a sub-network may be handled by a sub-network controller (SNC). As such, the SNC provides functionality for autonomous operation to maintain the sub-network in service for at least a limited amount of time in case of unavailability of the 6G ON. Because sub-networks are regarded as highly specific networks and tailored to their respective use cases, the SNC is envisioned to implement management functions that address the individual communication requirements of the SN-UEs towards the network. This may include interworking with time-sensitive networking (TSN), resource allocation, and positioning. In addition, the SNC provides gateway functionality for traffic entering and leaving the sub-network via the link to the ON.

The desired communication demands can be achieved by providing flexibility at the physical layer. For SN-UEs, different radio access technologies, such as 3GPP-based systems (i.e., 4G/5G/6G sidelink) or non-3GPP systems (i.e., WiFi, Bluetooth, ultra-wideband (UWB)) may be used depending on the configuration. For high performance applications requiring extreme reliability, non-contention-based access strategies on licensed spectrum with large bandwidths are required, as provided by 3GPP technologies in, e.g., the Frequency Range 2 (or FR2), meaning the millimeter wave (mmWave) frequencies between 24.25 GHz and 52.6 GHz.

With mobility as one of the key characteristics, sub-networks will allow for seamless roaming of SN-UEs across different sub-networks and to the ON, as well as the mobility of the sub-network itself. Additionally, the nesting of sub-networks (i.e., a sub-network inside another sub-network) is also a possible feature that allows a more flexible form of communication in, for example, an automated factory site.

Related designs for sub-networks have been discussed in academia [33] and standardization [34]. In 6G-ANNA, we enrich these approaches with our visions and expertise in the consortium, collect requirements for our use cases, and develop solutions that enable sub-networks to fulfil the demands, ultimately contributing to and shaping the standardization of 6G.

3) RESILIENCE

The term resilience stems from the Latin verb "resiliere", which means "to bounce back". Most definitions of resilience concentrate on the ability of a system to "bounce back" after the changing and challenging conditions while restoring a level of service within a suitable time upon the degradation [35][36]. NextG Alliance defines resilience concerning 5G and 6G networks as the "network's ability to meet a diverse set of service objectives and to be able to identify, anticipate, detect, and respond to the evolution of the state of the network." [37]. By adapting and recovering, resiliency shall provide the means to provide reliable operation and high network availability. For systems requiring high resilience and availability, redundancy and the so-called hardening are the tools used to achieve this requirement for critical infrastructure. APCO International, an organization of public safety communications professionals, has provided a Guide for Public Safety Grade Site Hardening of the network infrastructure, approved by ANSI, and shows the effort and costs involved in hardening a network against environmental risks [38]. For example, immediate and long-term backup power sources induce costs that increase with the number of sites requiring hardening. In addition, the critical infrastructure must adapt on the fly to challenging conditions and be easy to use. It should be able to add capacity where and when needed, at short notice, to provide temporary coverage for remote areas where no grid power supply may exist, and to offer new ways to connect back to the network to ensure that people remain connected [38].

The 6G concept as a Network of Networks, including sub-networks, offers the opportunity to increase the resilience of networks and provide alternative means for costly physical hardening concepts. In particular, 6G-ANNA plans to ensure the resilience of autonomously functional sub-networks, creating fallback options to avoid segmentation. Fast and efficient handovers will be orchestrated using artificial intelligence and automation solutions. Furthermore, 6G-ANNA will go beyond maintaining transport services and offer resilient storage services by leveraging and incorporating in-network computing and an information-centric networking (ICN) approach. This includes the development of a corresponding architecture that integrates both communication and computing.

C. AUTOMATION

Automation generally refers to the automated operation and optimization of flexible, secure, and sustainable networks and related end devices while considering user requirements and needs. Since today's networks are complex to design and manage, partly because of the new technologies in wireless communications, and partly because of novel computing paradigms, such as computation based on digital twins (see Section III.D), automation needs to be accompanied with "simplification" in network management for any 6G system that is expected to generate and process immense amounts of data. New applications and services, such as the exploitation of robots for various medical interventions [39], using holograms in communications [40], and massive latency-critical Industrial Internet of Things (IIoT) [41], etc., in addition require the management of demanding traffic needs in terms of different metrics of interest, which span beyond the bandwidth, such as energy efficiency or privacy. Complying with these requirements is not possible in current cellular networks [42], and they present a major challenge for 6G.

The use of digital twins, discussed in more detail in the rest of this section, as a relatively new concept in automation, is considered beneficial for optimal resource allocation in the next generation of cellular networks, especially in industrial applications. In many cases of optimization, resource allocation policies need to be changed across several dimensions (physical resource blocks (PRBs), computing resources, etc.). This involves solving different optimization problems in a traditional manner and with the help of machine learning and AI.

AI/ML has been acknowledged as one of the main enablers to achieve significant improvements in network automation. This is especially visible in scenarios in which the entire network is expected to self-adapt and self-react to changes and disruptions with minimal or no human intervention. 6G-ANNA aims to identify the most effective and trustable models that solve specific problems and meet the automation requirements, along with aspects of network predictability.

The other side of AI/ML is its increased usage in advanced applications, including predictive maintenance for machines, digital healthcare, and indoor localization in shopping malls. In the future, the vast distribution of such AI-driven applications must be appropriately addressed by the 6G network. Thus, 6G-ANNA is working on efficient methods for distributed training (e.g., Federated Learning [49]) and the execution of neural networks via edge computing resources in the network, as this is the preferred deployment option for applications that cannot rely on cloud computing facilities (e.g., owing to strong privacy or latency requirements). Therefore, these methods must be designed in such a way that they work with limited compute and network capacities. Automating the configuration of the network in conjunction with such AI/ML applications is being addressed by 6G-ANNA. Automatically configuring the network according to specified application requirements can be addressed through intent-based networking, which is currently under discussion in multiple standardization forums, such as TM Forum[50], ETSI ZSM [51] and 3GPP SA5 [52]. Although intents are not a new concept of autonomous networks, the implementation of such autonomous capabilities is an open and challenging task.

In summary, the automation of 6G networks is of paramount importance for achieving desirable performance as well as large adoption of 6G networks. 6G network automation needs to consider all parts of the network (i.e., radio access, core network, central and edge cloud, etc.) to realize holistic and end-to-end optimized network operations.

D. DIGITAL TWINS & EXTENDED REALITY

A digital twin (DT) is a digital replica of physical assets, processes, and systems that are synchronized at specific frequencies and fidelities. DTs use real-time and historical data to represent the past and present, and allow the simulation of predicted futures.

While DTs have been in use for some years, for example, in the form of asset administration shells (AAS) in industry, for management and optimization in the network domain, and building information models (BIM) for the building sector, the potential and power of DTs increase with the timeliness and accuracy of the DTs. This requires concurrent updates based on real-world data, which are the basis of so-called digital shadows. In today’s systems, there are often limitations due to limited bandwidth, non-negligible delays, and computational limitations to efficiently process the huge amounts of data needed to keep the DT up to date.

6G can support real-time DTs in various ways: joint communication and sensing can be integrated to update the DTs, in-network compression to reduce the large amount of required data, precise positioning and mapping to generate an exact copy of the real world, and a tight integration of network and compute resources to allow for an efficient handling of DTs.

Network digital twins (NDT) offer benefits for planning, deployment, and operations. Interaction of NDT with factory applications and its digital twin enables us to carry out predictive analysis in the digital world for both runtime network optimization as well as for appropriately adapting the (factory) application behavior. Such a joint interaction of digital twins also potentially leads to fault identification and prevention.

While an NDT can be used for real-time optimization of the network, digital twins of factories can be used for optimization of production processes and logistics, and environmental digital twins can be used to create an immersive experience for extended reality (XR) users.

XR, as the umbrella term for virtual reality, augmented reality, and mixed reality, will change how we interact between the real and virtual worlds. Although Wi-Fi and 5G can already support XR users to a certain degree, a fully immersive experience requires 6G. Current XR devices are rather bulky, tethered to a smartphone, or connected to a PC. The reason for this is the compute intense rendering of virtual

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objects. To enable lightweight, energy-efficient devices, the computation must be offloaded to a nearby edge/proximity cloud, which must also be equipped with a powerful graphics processing unit (GPU). The downside of offloading is that it requires low delays, rather large bandwidth on both downlink and uplink, and privacy aspects must be considered as sensitive camera data is streamed. Thus, to enable an immersive XR experience, a close interaction between the XR applications, the underlying network, and the compute resources is required, which 6G-ANNA proposes to demonstrate.

6G-ANNA considers enabling real-time digital twins and an immersive XR experience based on a precise positioning and mapping service. Depending on the use case, the precision should be up to the centimeter level and 1° accuracy. This requires a fusion of various radio- and vision-based positioning mechanisms. To allow real-time updates of the digital twins, the mapping service should also work in real time, meaning that changes in the environment are detected immediately and adjusted in the maps used by the digital twin.

E. SUSTAINABILITY

A sustainable network is one of the key requirements of 6G. Having a sustainable 6G architecture that can provide performance guarantees on multiple, usually very stringent, QoS metrics and for different use cases is of paramount importance [42]. The trade-off between sustainability on the one hand and reconfigurability, on the other, is a critical issue that needs to be addressed. To address this challenge, adequate models that can capture the largest possible extent of power consumption as a function of various traffic parameters are needed. These models, or the analytical results obtained from them, will be validated in 6G-ANNA with real measurements from testbeds.

The reduction in energy consumption targeting 6G networks has already been considered in [43], where the achievable performance is compared for different power control methods. Alternative methods [44] emphasize the need to use AI/ML techniques to minimize energy consumption and to use intelligent reflecting surfaces. Intelligent reflecting surfaces were also proposed in [45], together with exploiting cell-free and airborne access networks, with the ultimate goal of achieving an energy self-sustainable 6G.

6G-ANNA plans to also introduce energy savings in other ways. For example, depending on the traffic load in the network at certain periods of time and to maintain low energy usage, an automated decision to shut off certain edge clouds and reassign the tasks to other edge clouds can be made. Alternatively, certain User Plane Functions (UPF) can be shut down and the traffic from the base stations can be redirected to other UPFs of the core network to save energy. In both cases, these decisions can be seen as solutions to optimization problems, where the constraints are the QoS requirements of the users, with the objective of minimizing energy consumption. Solving these optimization problems and obtaining the corresponding algorithms for sustainable policies are the focus of 6G-ANNA.

F. SECURITY

Thus far, 4G networks have been remarkably robust to any type of attack. 5G networks build on this field-proven technology and add additional security features, for example, for better protection of permanent subscriber identities. However, it cannot be denied that for 6G, the attack surface of mobile networks increases because of more features provided by the networks, more complex software, use of AI/ML, more diverse network structures, and more heterogeneity of platforms and stakeholders. At the same time, more critical services rely on networks, attracting more, and more capable attackers.

The trend of virtualizing network functions and running them on cloud platforms rather than on custom hardware brings specific security challenges, particularly if a cloud is not exclusively used by a mobile network but also hosts other workloads. Methods for reliable isolation of workloads, guaranteeing availability of an agreed amount of resources, and ensuring the integrity of the platform and software stacks at boot and during runtime are needed. 6G-ANNA analyses the state-of-the-art, identifies potential gaps, and works on improving and automating the applicable security mechanisms. It also considers secure workload orchestration and management, including attestation techniques and fine-grained continuous monitoring of the overall system and its components.

A specific challenge arises when workloads need to be deployed in data centers that are not fully trusted, so data must be protected against the data center operator during processing. 6G-ANNA will provide a secure runtime environment for containerized 6G services using confidential computing techniques. Thus, the cloud operator is excluded from the trusted computing base. The runtime environment provides integrity and confidentiality for data at rest, in use, and in transit as well as remote attestation for integrity verification. Another key aspect is the automated and secure orchestration of containerized workloads in heterogeneous cloud environments, for example, utilizing Kubernetes[16]. To achieve a small overall code size and strong isolation guarantees, the OS-level virtualization platform GyroidOS[17] [46] and the microkernel seL4[18] [47] will be used.

The increasing reliance on software components calls for verified, secure software that also allows fulfillment of increasing compliance obligations. The software

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[16] https://kubernetes.io/

[17] https://gyroidos.github.io/

[18] https://sel4.systems/

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development process must include steps and tools to automatically ensure security and compliance. To cope with the task to perform compliance tests frequently, that is, not only per major release, but also each time the system is updated (e.g., a security patch is added), 6G-ANNA aims to provide tools for the automation of compliance testing.

AI/ML is expected to be used pervasively in 6G networks, and threats, such as data or model poisoning or interference attacks, must be considered. As many potentially sensitive data may need to be processed to generate ML models, privacy is a specific concern; therefore, techniques such as federated learning or privacy-preserving feature extraction must be considered. 6G-ANNA investigates how to properly secure the complete AI/ML pipeline, resulting in AI/ML systems that are not only efficient and scalable, but also privacy-preserving and secure.

In contrast, AI/ML provides a significant opportunity to improve network security by efficient early detection of anomalies and attacks. 6G-ANNA will provide a system that enhances classical methods for traffic classification and anomaly detection using AI/ML methods, such that attacks can be detected efficiently even in huge data streams, including ciphered traffic. Detecting suspicious behavior allows a more detailed analysis, and if needed, mitigation measures will be proposed, or, in the case of full automation, immediately triggered.

Considering the timeframe for 6G, the threat posed by quantum computers breaking all public key cryptography used today is highly relevant. Luckily, research on quantum-safe, or “post quantum” algorithms (PQAs) is well underway. However, the potential impact of adopting PQAs on mobile network performance is not yet well understood. 6G-ANNA will investigate in depth the performance properties of different PQAs and their suitability for various use cases, including those where the capabilities of the end devices are restricted; however, the security requirements are still high.

In light of cryptographic methods being endangered by quantum computers, Physical Layer Security (PLS) methods may become important for 6G. PLS is an opportunistic technique for designing security algorithms based on channel reciprocity, which is inherent to wireless channels between legitimate communicating nodes. This privilege is not shared by the eavesdropper, which is located at a distance of at least half the wavelength of the carrier. This principle can be used to extract secret keys, perform authentication, etc., which can complement the security protocols running in the upper layers. Furthermore, it is possible to design an intelligent and overhead-aware security framework that uses computationally intensive upper-layer security protocols only when PLS indicates a problem. A specific PLS technique investigated in 6G-ANNA in the context of wireless ad hoc networks is friendly jamming, where the wireless channel is continuously jammed in a controlled manner so that only authorized devices can cancel the interference and recover the signals carrying the communication. The use of intelligent reflective surfaces (IRS) is another technique to be explored in 6G-ANNA to improve PLS performance. By intelligently configuring the IRS, transmission to a legitimate user can be enhanced while suppressing transmission to the eavesdropper, resulting in a significant improvement in security.

6G-ANNA envisions that future 6G networks will support the integration of sub-networks that may use diverse wireless technologies and may be operated by various stakeholders. There are many use cases for this, including public safety. Security is an obvious requirement in this context, and 6GANNA will investigate how networks and stakeholders can interact to provide sound security in a highly dynamic network of networks. A special aspect is the integration of PLS in the network of networks case, which may meet stringent security requirements in industrial contexts.

The need for strong privacy calls for specific so-called Privacy Enhancing Technologies (PET), which are important in the context of AI/ML, as mentioned above. In particular, homomorphic encryption allows outsourcing data processing to a third party without revealing the data or processing results in the clear to the third party. 6G-ANNA will implement an algorithm using deep neural networks for either data cryptography and compression and investigate the trade-off between resource costs and performance when using homomorphic encryption. Another approach in the field of PET is the concept of an “anonymous network” that aims to minimize the amount of private user information revealed to network nodes. 6G-ANNA investigates how to improve such methods and how to best apply them in 6G networks, particularly in the context of network of networks.

One aspect of holistic security for the 6G infrastructure is physical security, that is, controlling physical access to hardware components. With the rise of edge computing, a greater number of devices are expected to be deployed in public or shared environments, at the cost of a greater risk of physical tampering. 6G-ANNA will investigate methods for securing critical hardware at a system level. Examples of such hardware are fixed access points or radio station components. Anti-Tamper Radio (ATR) [48] is a promising technology for system level hardware tamper detection. ATR works on the radar principle, using microwaves to sense the physical environment. The ATR sends a special radio signal that spreads everywhere in the system and is reflected by the walls and hardware components. All of these reflections cause a signal to reach the receiver, which is as characteristic of the system as a fingerprint. Tiny changes to the system are sufficient to have a noticeable effect on the fingerprint. Here, the radio fingerprint can be analyzed using ML/AI to extract information about the physical integrity of the hardware and take necessary countermeasures, if required. The magnitude of change required to trigger the anomaly detection is calibrated at initialization and automatically adjusts to environmental changes.

IV. EVALUATION

The 6G-ANNA project will not only focus on concept work. The most relevant concepts developed in 6G-ANNA will be implemented, demonstrated, and optimized (where applicable) in the following Proof of Concepts (PoCs). These are (as structured per topic):

6G-Access

- Slice-oriented radio access network with synchronized transport system
- ML-based PHY layer transceiver functionalities on the open platform of the 6GEM research hub[19]
- 6G in production environments using a distributed load generation system designed in 6GEM
- 6G wireless fingerprinting for anomaly detection in production facilities and proximity detection for occupational safety

Mobility

- Intra- and inter-communication of vehicles
- Secure communication between drones
- Subnets for drones and vehicle

Safety & Resilience

- Advanced end-to-end security based on 6G-specific functionalities for critical services, including air-cab connectivity for ground control
- Dynamic placement of functions (including replicas) to optimize energy efficiency

Digital Twinning

- Real-time digital twin for automation in production environment
- Application of digital twins for vehicles (automotive) or in-vehicle sub-networks
- Digital twins for network optimization and resource management

Extended Reality (XR)

- XR applications via 6G in robotics for remote teaching, user training, and/or plant prototyping
- 6G XR platform for processing, rendering, and positioning XR services

Production

- Over-the-air updates in manufacturing and automotive environments
- Management and optimization of heterogeneous networks and industrial edge computing resources for running distributed applications and AI

For this purpose, various testbeds are provided by the project partners, ranging from production halls to mock-ups (e.g., an air cab) and mobile radio testbeds to a drone test site. Furthermore, collaboration with the testbeds of the 6G research hubs is planned.

V. CONCLUSION

The German lighthouse project 6G-ANNA contributes, based on its vision and research activities, to the definition of an 6G E2E architecture and system design with a focus on German and European use cases and scenarios.

In this article, the main research directions of 6G-ANNA are described, including 6G RAN, network of networks, automation & simplification, digital twinning & extended reality, security, privacy and sustainability.

Based on the project use cases, the planned areas of evaluation, 6G-Access, mobility, safety & resilience, digital twinning, extended reality, and production were defined.

By mid 2024, the 6G-ANNA project is entrusted with providing a detailed description and analysis of the technical concepts proposed in this paper. By the end of the project (June 2025), the project partners plan to extend and refine the technical work and testbeds/PoCs, and to provide final evaluations and large-scale demonstrations of the proposed solutions. 6G-ANNA activities will be aligned with the other 6G research and industry projects in Germany and Europe via the German 6G platform, as well as more broadly aligned with global efforts in next-generation mobile networking.

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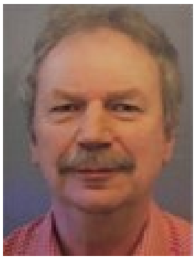

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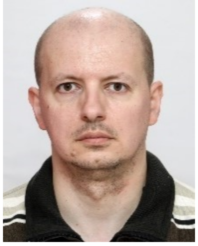

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