6G Architectural Trends and Enablers

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***Abstract*— By 2030, the next generation mobile network (6G) is expected to be ready. Currently, as work on 6G is being ramped up, prospective technical components are being explored with objective to fulfil challenges and requirements expected for 6G. In this paper we address the important task of reevaluating and evolving the network architecture, to ensure that performance, e.g., data rates, coverage, energy efficiency, will support use cases, both current and future, while minimizing total cost of ownership (TCO). This task includes aspects of cloudification, where shared generic hardware replaces dedicated hardware to improve flexibility and reduce TCO, jointly with cloud-optimized network architecture, as well as more flexible deployments expected for 6G, for instance, macro base stations, mesh networks, satellites, private networks, and connectivity using sub-THz frequencies, which are expected for 6G. Given this range of deployments, the network will need novel procedures for mobility to ensure reliable and resilient connectivity with unprecedented performance.**

Keywords—6G, network architecture, AI, cloud, D-MIMO, programmability, mobility

I. Introduction

As the fifth generation (5G) of mobile networks is being deployed and expanded, and the 3GPP standardization working on the third 5G release, progressing towards 5G Advanced, research on the sixth generation (6G) of mobile networks has already begun [1]. The initial work has started shaping the vision and exploring prospective technological enablers for the next generation networks, which are expected to be commercially available by 2030. As mobile networks become increasingly ingrained in our societies, addressing more and more sensitive, critical, or essential services and use cases, the requirements and expectations of the networks will go beyond mere technological performance. For instance, the European flagship 6G research project Hexa-X has defined key values such as *sustainability*, *trustworthiness,* and *digital inclusion* in order to capture these aspects [2]. To address these new requirements, the research on prospective enablers include, for instance, distributed MIMO (D-MIMO) [3], pervasive artificial intelligence (AI) and machine learning (ML) [4], joint communication and sensing (JCaS) [5], reconfigurable intelligent surfaces (RIS) [6], and sub-THz communication in the 100-300 GHz band [7]. The expected increase in performance along with the integration of the novel technological enablers will require a revisitation of the network architecture, evaluating which aspects can be maintained and which need to be redesigned or added. This paper is structured as follows: section II describes the envisioned new 6G architectural trends and requirements, and section III describes potential 6G architectural enablers suited to address these requirements. Finally, concluding remarks are presented in Section IV.

II. 6G Architectural Trends and Requirements

The 6G architecture is expected to be shaped by the use cases and the requirements accompanying the use cases, while at the same time being flexible to be able to support use cases yet to be invented. To this end, this section is devoted to summarizing the pioneering use cases that will enable shaping the 6G architecture.

A. Cloudification

With 5G, 3GPP enabled a cloud friendly 5G core network (CN) implementation, where the so-called Service Based Architecture (SBA) is based on the principles of network services offered by network functions (NFs) communicating via web-based APIs. The cloudification trend is expected to continue for 6G bringing novel network design, e.g., cloud-optimized network procedures can be obtained considering NFs capable of accessing any (authorized) network information with limited (or no) hierarchical interactions among NFs. The key challenge is to design a future 6G architecture that can fully utilize and interact with the cloud platform with regards to speed of development and reuse of common cloud components, balancing the need to standardize business-critical interfaces with the fast evolution of IT tools, such as DevOps.

B. Efficient networks - Strive for Simplifications

A new smart connectivity platform capable of fulfilling 6G key values will require an architecture that can integrate legacy networks and mission-critical networks while increasing dependability, coverage, and reliability. Important areas to investigate and develop for 6G research are, for instance, determining the right level of modularization, focusing standardization on the basic functionality while ensuring that it is possible to build more advanced functionality on top, e.g., using network programmability. Integrating and leveraging such architectural trends from the onset of the 6G concept development is expected to increase flexibility and cost efficiency, while at the same time strive to decrease the overall complexity.

C. Flexible deployment in the 6G time-frame

The deployment of mobile networks has become increasingly complex and diverse with every new generation. During the 4G standardization there were many discussions about so called HetNet solutions, i.e., how networks with both wide-area macro and small-cell Pico base stations should cooperate, while the extension of the radio spectrum into mmW in 5G added yet another aspect to flexible deployment.

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For 6G it is believed that spectrum between 100-300 GHz will be a part of the standard. Therefore, 6G deployment will include nodes using higher frequencies with limited coverage as well as nodes at low frequencies with seamless coverage, as illustrated in Figure 1. Furthermore, the number of network solutions for capacity and coverage is also expected to increase in the 6G timeframe. This includes solutions such as D-MIMO networks, Non-terrestrial Networks (NTN), mesh networks and cloudification of the network elements. Therefore, the Hexa-X project works under the assumption that 6G will consist of many diverse types of networks, sub-networks, and 6G will be a Network of networks [2].

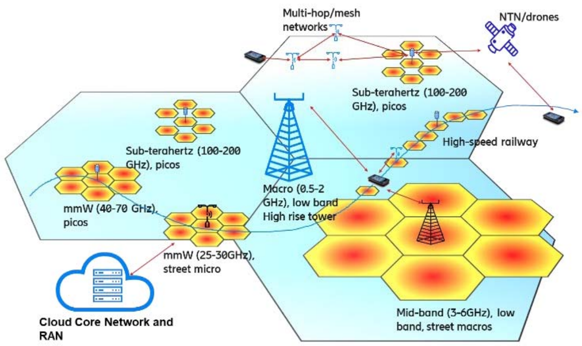

Figure 1 Flexible Deployment: 6G networks as network of subnetworks with wide range of deployments and network solutions.

However, as mobile broadband is becoming increasingly critical to society, the architecture of 6G must support reliability and resilience beyond 5G, both in terms of service and infrastructure provisioning, when connecting though any of the diverse connectivity options.

D. Dedicated networks and faster time to market

The concept of (non-public/dedicated) private networks refers to isolated network deployments for the dedicated purpose of enterprises, where only authorized user equipment (UEs) that are owned by that enterprise can access the private network. Private networks also enhance the security aspects due to the isolation as well as the fact the UEs of the enterprise can be restricted to use only the private network. Among many, a benefit of such deployment is the expectation of a flexible network that can be tailored for specific requirements of the enterprise.

5G is the first generation of mobile networks that is natively designed to offer networking services beyond Enhanced Mobile Broadband (eMBB) to address also Massive Machine-Type Communications (mMTC) and Ultra-Reliable, Low-Latency Communications (URLLC). In addition to this, 5G features such as network slicing, edge computing and SBA have facilitated the design and deployment of private networks for a variety of use cases and enterprises. 6G is expected to address manifold use cases, hence requiring tailored network features to address the specific needs of each use case. A limiting factor for achieving the full potential of network adaptability in mobile networks is that introducing features having impact on multiple network entities requires standardization, that takes considerable time and effort. To achieve network adaptability, 6G requires a framework to introduce features rapidly thus enabling a faster time to market. Capitalizing, partially, on the software defined networking (SDN) principles, a programmability framework for mobile networks that gives the possibility to not only program specific features in a single network entity, but also to program more innovative features, having impact on air interface protocols, will unlock the potential for network adaptability. For example, programming a tailored control-plane procedure for industry sensors/IoT devices connected to a dedicated network to optimize the performance in a factory automation scenario.

E. AI in 6G

Thanks to the enormous development in computational resources, AI can now be applied to almost every aspect of mobile networks. One of the main benefits of AI is the possibility to reduce the need for human interaction and instead rely on AI operations using a data-driven architecture. AI is expected to optimize the 6G communication and use 6G as a tool for AI, i.e., AI as a service. Possibilities for using AI span different network entities and layers of the radio stack throughout the whole mobile network. AI is expected to be able to optimize e.g., physical layer, mobility algorithms, management of the networks, QoS, etc. Towards the 6G time frame, the trend is a deeply integrated AI, a fundamental enabler for communication, guiding how network components behave and communicate, rather than a tool for optimizing and tuning network parameters as implemented in previous generations. The research community has already shown the feasibility of deploying AI models to implement and assist various network functionalities [8].

III. 6G Architectural enablers

A. Cloud RAN and CN solutions

With a cloud-native network, the RAN and CN architecture should be possible to streamline, i.e., reduce some complexity. In cloud environments, complexity could arise with hierarchical interactions among NFs, multiple processing points for a certain message, duplication of functionalities among functions, etc. In 6G, hierarchical interactions might be reduced if, for instance, a network entity/NF could access any network service or relevant network data, without the need of relying on intermediate entities/NFs. The number of processing points might be reduced by redesigning network functionalities with the aim to perform all relevant processing for a certain network task in a single point. This might result in a different placement of network functionalities among network entities and NFs, as well as to a possible reduction in the number of entities and NFs, consequently moving towards fewer business-critical interfaces.

One example of a streamline opportunity is related to signaling. In 5G, signaling of a typical procedure involves the UE, gNB, and usually several NFs in the CN. Figure 2 shows an example of how a particular action involves several interactions between different NFs, all of them activated in sequence since the current network architecture is hierarchical. This action could, e.g., be a handover request and handover execution and involved NFs would in that case be Access and Mobility Management Function (AMF), Session management Function (SMF) and the User Plane Function (UPF).

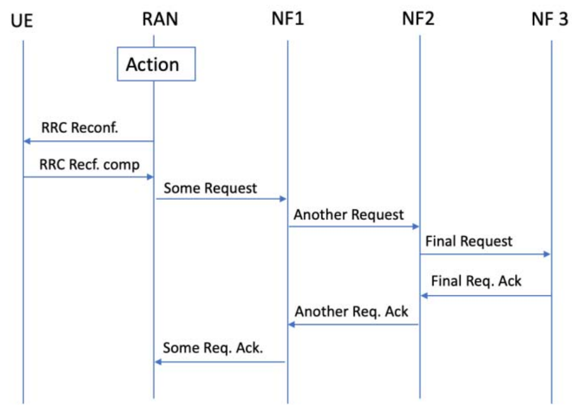

Figure 2 Principle of signaling flow in current networks.

With a cloud-native design of the CN and RAN, it should be possible to perform the requests to NFs in parallel and, hence, optimize the overall signaling speed. Figure 3 shows an example of how the particular action can be simplified in a cloud-optimized network architecture without the hierarchy between NFs. In this case, RAN could directly notify the different NFs about the event. Overall, the example in Figure 3 leads to a more efficient use of signaling resources and is future proof (if other CN services need to be added).

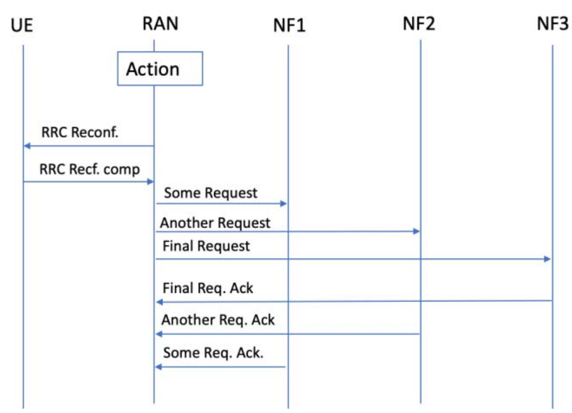

Figure 3 Simplified signaling for the same action in a future network.

B. *Sustainable growth with reduced total cost of ownership and enhanced energy efficiency*

6G is expected to be a crucial enabler in ensuring sustainability and taking responsibility on a global society level. For these reasons, sustainability is investigated under two different topics relevant to ICT and 6G, as Sustainable 6G and 6G for Sustainability [9]. A key challenge for 6G will be to break the energy curve, i.e., to suppress the total energy consumption with increasing traffic 6G for Sustainability will aim to minimize energy and resource consumption, reduce emissions, and enhance social aspects, which require enhancement in the world. In our view, 6G is expected to help realize three different goals from the Sustainable Development Goals proposed by the United Nations [10]: Industry, Innovation and Infrastructure, Quality education, and Decent Work and Economic Growth. The requirements will be satisfied by key 6G features such as comprehensive coverage, affordable infrastructure, more powerful smart devices, and AI-driven research ensuring high quality, sustainable, and resilient infrastructure. Comprehensive coverage will make education and job training categorically accessible throughout the world rather than only eliminating dead spots and spotty rural coverage. 6G will provide industrial growth by creating new jobs and career paths and will presumably exploit low-cost hardware by fulfilling the requirements of some of the longstanding challenges of current device design.

A mobile operator's total cost of ownership (TCO) for a cellular network includes both capital expenses (CAPEX) and operating expenses (OPEX). Typical capital expenses include RAN/CN and transport equipment, site construction and equipment, installation costs and site acquisition. Typical operating expenses include costs for a leased line, dark fiber rental, spectrum for wireless transport, site rental, energy consumption, operation and maintenance costs and vendor support. According to GSMA [11] about 20-40% of OPEX is energy consumption. Thus, reducing energy consumption is important for the economy of the network. Increased traffic volumes (in future cellular networks) are likely to lead to higher energy consumption. Some of this increase can be mitigated by more efficient hardware. However, even if more efficient hardware can mitigate the increased energy usage needed for wider bandwidth, the use of higher frequencies will demand a denser network where each RAN node consumes energy, which will affect the total energy consumption in the network.

C. *New mobility components*

This section describes some of the functionality and components necessary to support the new use cases and requirements of a 6G network from a mobility aspect.

1) *Integration of RAN nodes with new spectrum*

In 6G, the deployments will encompass a wide range of different cells and frequencies, for example, macro cells using low frequencies with wide coverage and Pico cells using the higher frequency bands with rather spotty coverage. Furthermore, it is expected that existing solutions, such as dual connectivity (DC) and carrier aggregation (CA) will be important to integrate higher frequencies and to ensure high reliability mobility also for higher frequencies. One possible way forward is a flexible multi-connectivity solution, i.e., more than two nodes involved, e.g., one master node and two secondary nodes. The different connections should be decupled in DL and UL, so one can for example use three DL connections but only one UL connection. A general disadvantage with the DC solution is the 3GPP specification complexity, so care needs to be taken to not introduce too much complexity. Other ways to ensure reliable mobility may be to use mesh networks, where, for instance, integrated access and backhaul (IAB) nodes can create a dense network without the need for wireline fronthaul and backhaul. Thus, there will likely not be one single mobility solution, but several solutions combined are needed to fulfill the coverage and reliability requirements of 6G.

2) *Integration of non-terrestrial networks*

Non-terrestrial networks (NTNs) could provide coverage to exceptionally large and/or isolated areas at a lower cost compared to terrestrial networks (TNs). NTNs can provide a low area capacity which suits rural areas and widely distributed IoT networks with a small infrastructure [12], [13]. For urban areas, there will always be a need for TNs to deliver the performance and fulfil capacity requirements. NTN is not limited to satellites, but also includes drones and High-

Altitude Platform Station (HAPS). In 5G, there are three types of architecture options for NTN: Transparent, Regenerative payload, and Hybrid as shown in Figure 4. Transparent is the simplest type, where the NTN serves as a relay of the radio signal between the UE and the gNB on the ground. Regenerative payload implies that the satellite can generate new packets, which is equivalent to having gNB functions onboard the NTN node. For the RAN-split hybrid solution, low-layers of the gNB protocol stack, i.e., DU (Distributed Unit, are on-board whereas the higher-layers, i.e., CU (Centralized Unit), are on the ground. The main advantage of the transparent architecture is that hardware is not necessary to support a full gNB, which means that the weight of the NTN node can be lower, whereas the main advantage with the regenerative architecture is that the NTN node can have more complex behaviors. In the latter case, several RAN protocols terminating in the gNB will experience a lower propagation delay since the signal does not have to reach the ground again and can cover areas where a ground station cannot be built by using inter-NTN node links and multi-hop.

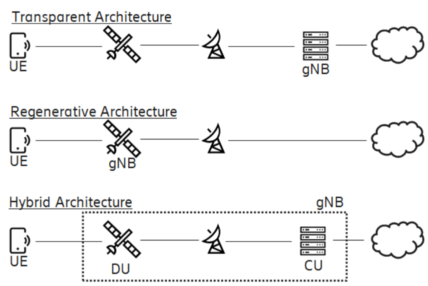

Figure 1: Main options for NTN architecture in 5G/6G

In 3GPP in Rel-15/16, several studies have been carried out to assess the feasibility with NTN and the viable solutions to apply to the standard [14], [15]. Further on, there has been a moderate update of the specification to enable NTN support for eMBB and mMTC devices for low frequencies or devices with external high-gain antennas at high frequencies. For the case of satellites, enhancements include improved synchronization due to doppler fading, improved HARQ (Hybrid Automatic Repeat Request) processes due to long propagation delay, etc. It is expected that more advanced NR (New Radio) features will be standardized at a later stage, or in the 6G timeframe.

3) Distributed MIMO

Large scale D-MIMO may be a component for 6G systems, due to the potential improvements in spectral efficiency and ubiquitous radio access [16]. Apart from coordinated densification and macro-diversity overcoming the path-loss and removing the blocking effect for uniform performance, it may also realize robust access links, supporting mobility on high frequency bands where the propagation environment is more challenging. Enabling techniques for scalable distributed large antenna systems, distributed intelligent processing, smart connectivity platforms including architectures and topologies are currently being investigated in the Hexa-X and Reindeer projects [3], [17].

D-MIMO and Dynamic Point Selection (DPS) can act as L1/2 mobility techniques assuming that the mobility is handled at the Physical (PHY) and Medium Access Control (MAC) layer. This means that the UE does not need to update the Radio Resource Control (RRC) configuration while in the pre-defined area, the UE continues to use the same configuration as before. The L1/2-mobility relies on a system with several access points (APs) connected to a CU via a high-capacity fronthaul transport network. The APs will be organized in a so-called MIMO cluster, where they are all connected to a single CU. Ideally, the UEs in the MIMO cluster area are connected to all APs at once. However, for complexity and resource utilization reasons, it may be beneficial that the UEs only connect to a subset of the APs, which is referred to as the serving AP cluster of the UE, as shown in Figure 5. This means that the UE must still select one or multiple APs in the area best suited for transmission and reception.

Dynamic AP-UE association techniques following a user-centric approach, updates the serving AP cluster for each user and can reduce the number of unnecessary handovers, which would require time-consuming signaling [18]. Having an AP cluster updated, the precoder needs to be updated. Yet more during the mobility, precoder weights need to be updated due to fast fading, based on channel estimation periodicity which can be done at APs locally. However, the AP cluster does not need to be updated as frequently as the precoder since the main driver affecting AP-UE association is the slow fading which depends on the distance to the APs.

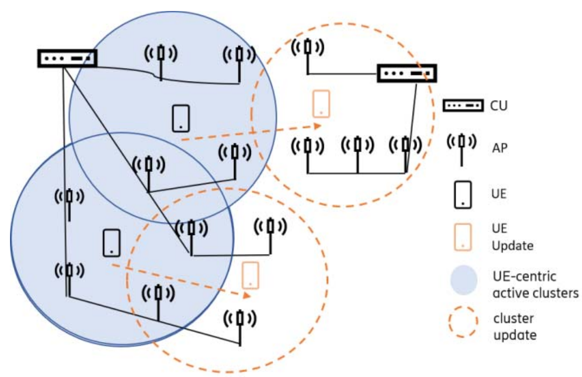

Figure 5: Illustration of D-MIMO cluster and serving AP cluster update

D. Network and UE programmability

3GPP plays a significant role in the success of multinational mobile communication by developing technical solutions oriented around interoperability. Due to study/work item cycles, it usually takes a long time to introduce new behaviors and functionalities. Moreover, additional delay is inevitable due to the time gap between standardization and time-to-market. The associated cost is well justified for major changes introduced to the mobile networks as success relies on standardization procedures. However, introducing features with limited impact, e.g., a feature requiring changes only to a limited number of network entities, has proven to be unnecessarily slow. Network programmability is a complementary approach to how new features can be introduced and/or improved to enhance network capabilities, services, control, and management, especially targeting those cases where new/improved features can be introduced with changes to only a limited number of network entities. Today's principles of network programmability are shaped through the contributions of efforts, such as, active networking [19], [20], separation of control plane (CP) and user plane (UP) for traffic engineering [21], [22], OpenFlow [23] aiming at programmable configuration of routers and switches and, most recently, P4 (programming protocol-independent packet processors) [24] programming language developed for enabling a programmable UP.

It is only recently that the concept of programmability in mobile networks, i.e., the CN and the RAN, is being considered and it has accelerated with the advent of 5G. In 5G, leveraging on service-based architecture (SBA) has enabled to open up to a more straightforward introduction of new services. With SBA, network functions offer services to consumers providing a twofold opportunity. On one hand, a network vendor, or a network operator, or a third party acting as an application function (AF), can build new services leveraging on those offered by 5G network functions. On the other hand, a network function (NF) provider can enhance the NF with a new service and make the necessary APIs for that service available to other NFs to be used when and where deemed appropriate.

The NR air interface is designed to be highly configurable with a multitude of features to satisfy the requirements of multiple services. However, introducing new features that have an impact on the air interface protocols is time-consuming, as changes should be applied to both UE and gNB. This becomes an even greater concern in private networks where enterprises often ask for a tailored solution. With the digitalization of the industry many niche use cases will emerge which may not motivate standardization to address them all efficiently. UE programmability [25] may be an enabler to help realize the vision of fit for purpose promise of dedicated networks for both legacy and upcoming use cases in 6G. A programmable UE in private networks, as seen in Figure 6, enables introduce of new features fast, support manifold use cases, custom tailored solutions for verticals and maintain and add new features to UEs that require operation over a long horizon. The scope of programmability should be defined with respect to what is intended to be accomplished with UE programmability to strike a balance between pragmatism and vision and address needs and requirements from multiple parties.

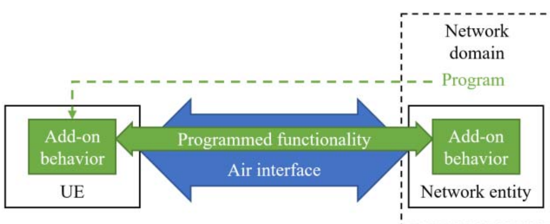

Figure 6: New functionalities and behaviors are introduced to the UE's air interface by programming it on the fly.

E. New architecture for AI

One of the fundamental aspects anticipated for 6G is the capability to adapt the network quickly and dynamically in a fine granular way, considering both local and global changes in characteristics and requirements of services and infrastructure provisioning. A 6G network can be seen as a network of subnetworks, each tailored to address specific needs and thus having specific features and functionalities. A local or regional transformation may occur only in a certain subnetwork, and within the subnetwork it may apply to a single cell or affect neighboring cells. As the network is flexible and reconfigurable, the cost for the transformation may be reduced by applying AI-enabled optimization techniques. With the help of the local data collected by each subnetwork, AI-enabled closed-loop optimization techniques may be exploited for the local and dynamic update of the subnetworks. An example where an AI-enabled closed-loop optimization technique can be a vital component is network slicing, which will play an integral role in resource sharing and is capable of efficiently serving multiple vertical applications on a shared infrastructure [26]. However, existing slicing methods have only been optimized in a rigid way considering a case-by-case basis to satisfy the demands of various applications. The new 6G slicing must be on-demand and operating in an autonomous manner, in which AI has arisen as a fundamental ingredient for successful implementation and operation. The network slice is expected to be software-defined and self-evolving with the help of AI, which will allow bundling network functions intelligently to form the specialized network slices according to specified demands. Then, it will adjust or update network slices according to the dynamic changes of the wireless conditions, service requirements, and mobility patterns in an autonomous and intelligent manner.

Additionally, for any local change in the low layer protocols, the communication pattern/model between subnetworks may be replaced by a new communication pattern/model. For this purpose, recent advances in AI-enabled optimization techniques, such as, for gaming and learning approaches, may guarantee convergence in the lifetime management of the subnetworks. On the other hand, a local update of subnetworks requires a robust control plane to maintain the interaction between the subnetworks. Therefore, with the help of AI-enabled optimization techniques, impact of changes could be firstly evaluated partially on a subnetwork level and then widely on multiple subnetworks through network-level optimization/learning techniques. From this point of view, the architecture of 6G networks is expected to natively support AI-driven solutions for subnetwork adaptation and for inter-subnetwork closed loop.

Adding AI to the physical layer enables predictions regarding channel state information, protocol stack learning, resource allocation, and assistance of mobility-related decisions with predictions, such as, signal strength of the cells, UE trajectory, and triggering handover. With the help of cognitive networks, it is expected to enable large-scale deployment of AI agents to guarantee service availability where ML and machine reasoning (MR) are embedded to ensure that systems are managed autonomously. For large-scale deployments of AI agents to function seamlessly, adaptively, and autonomously, first, the 6G architecture must accumulate conceptual knowledge and conclude the existing knowledge and data set by using MR techniques. Then, the information retrieved from operations and services must be evaluated to improve configurations, processes, and software. Moreover, since the success of the network is measured by its credibility by the people, the reason behind the decision should be clearly explainable and stated by the specific mechanisms, the decision process should be legal and ethical, and the decision should involve people if necessary. Since 6G is foreseen to have a data-driven architecture, the infrastructure must support data pipelines that take care of moving, storing, processing, visualizing, and exposing data from inside service provider networks as well as external data sources in a format adapted for the consumer of the pipeline, guaranteeing privacy and access to only authorized consumers.

The architecture requires new functional entities and protocol-wise enhancements to ensure AI-tailored communication. For example, considering the cases of transferable AI over the air interface between gNB and UEs (transfer of data for training, AI models together with model management data, data distributed inference and rewards, etc.), it is still to be understood which requirements should be supported, as well as the required enhancements on signaling and protocols for training, inference, and maintenance. This should consider the application of AI in different layers of the stack, as well as usage of different AI algorithms and approaches for training, inference, etc. Furthermore, training methods and AI algorithms are evolving fast as evident from recent breakthroughs [27], thus the signaling and protocol aspects should be adaptable to the pace of evolution and innovation for addressing updates in, for instance, training, model/data distribution techniques, loss minimization algorithms, and compression techniques.

IV. Conclusion

In this article, we present fundamental architectural trends and enablers for the 6G architecture and examine them taking into account expectations of a future NW, its capabilities and requirements. The future architecture should support, e.g., new mobility components, cloud RAN and CN solutions, programmability, and new architecture components for AI. We show that the mobile networks become more complex due to the demands anticipated in the 6G timeframe in terms of e.g., higher bitrates, capacity and reliability, sustainability, management methods, signaling mechanisms and TCO. To fulfil all 6G requirements, we see a network consisting of many specialized sub-networks, such as, mesh, NTN and D-MIMO networks. The new D-MIMO networks with L1/2 mobility as well as new multi-connectivity solutions are required to realize higher capacity and improved reliability, whereas new architecture components, such as, programmability and novel architecture for AI, are needed to support, simplify, and manage the network (network of sub-networks and dedicated networks) in an intelligent manner. Finally, a cloudification of RAN and cloud-native solutions can support efficient signaling between elements in a network of subnetworks architecture.

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