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Organic 6G Networks: Vision, Requirements, and Research Approaches

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ABSTRACT Building upon the significant number of already published 6G position papers, we are concentrating on the immediate next steps toward turning the research vision of software-centric networks into reality. This is accomplished, by summarizing and assessing the various requirements documents and providing a significant number of specific research directions and approaches in order to fulfill them. This article complements the existing body of work, by focusing on future core networks and their infrastructures, yet maintaining a system-level perspective and progressing in the direction of scoping key technology elements and providing high-potential research approaches for them. Additionally, we rigorously discuss the impact that different technological advancements have on the other parts of the system, to provide a coherent, end-to-end network understanding. This is in strong contrast to current approaches, where from the challenges, each research direction becomes independent and, thus, its advances are potentially cancelled out by the next technology in the chain. By maintaining this system perspective, the adoption of the different technologies becomes easier, as they are developed in unison. To address the requirements in a coherent, holistic, and unified way, we extend our high-level architecture concept named "Organic 6G Networks" towards a comprehensive end-to-end system. A holistic software-centric system, adapting the latest software development advancements from the IT industry. The Organic 6G network provides support for building a streamlined software network architecture and offers the next step on the path towards the development and specification of future mobile networks.

INDEX TERMS Mobile Networks, 6G, Core Networks, Organic Core Networks, Organic Networks

I. INTRODUCTION

AFTER over a decade of research and development, the fifth generation of wireless mobile communications (5G) is being deployed in commercial networks around the world. While operators and manufacturers compete for their share of the market, researchers already look beyond 5G and towards the potential technologies and applications of the next generation (6G). During the initial stage of technology development, a large number of position presentations and white papers are building up the expectations towards 2030. These expectations include the new communication environment and consider new levels of the traditional Key Performance Indicators (KPIs), such as delay and network capacity, as well as novel ones focusing on overall network reliability, energy consumption, resource efficiency, and end device velocity. Using these requirements, the different areas of research are motivated as parts of the overall 6G system, giving an initial direction for the system that should be achieved. However, a vision for the end-to-end network architecture, encompassing all the layers from infrastructure to the high level management and sufficient to meet the requirements we identify, has not been established. In this situation, while the research within the different domains reaches for the depths required to meet expectations, the potential for cross-optimization will be missed again. The result will be a patchwork of technologies and solutions, whose integration into a coherent system will be highly complex.

To be able to address the next step beyond the requirements, we present the Organic 6G Network (ON) as an architectural vision able to meet the demands of 2030 and beyond. ON represents a software-centric architectural approach, drawing its roots from the state-of-the-art services and IT developments, which are able to morph and adapt, grow and shrink dynamically as needed. In ONs, distributed and heterogeneous radio, compute, and network infrastructures converge into a coherent and resilient communication system, incorporating different access and transport network technologies (<6 GHz, Terahertz (THz), sub-THz and Non-Terrestrial Networks (NTNs)) customized for the diverse use cases emerging in both non-public, campus, and public networks. Beyond the 5G Service Based Architecture (SBA), ONs address the end-to-end application/service requirements with flexible aggregation and disaggregation, orchestration, placement, and morphing of network functions, based on state-of-the-art Internet software services concepts. They are agile, Artificial Intelligence (AI)/Machine Learning (ML) driven, self-aware networks, which can adapt, optimize, learn, and evolve. Information about its current state can be gathered and processed anywhere in the network, ranging from the user terminal, network edge, and central servers up to end applications, by using a new highly customizable telemetry & knowledge exchange layer. Based on this vision, a set of key technology enablers and their high potential development approaches are described, providing a set of directions, which future research activities can follow. Finally, we present a high level 6G network architecture suitable to encompass the different key technologies and to provide a coherent, yet flexible view.

This article takes the next step forward from goals and use cases towards defining requirements and a direction for development. It is organized as follows. First, Section II presents the state of the art, discussing use cases and related work towards 6G networks. A review of previous networking approaches is provided in Section II-C. In Section II-D, we provide an overview of the technological premises driving the progress towards future mobile wireless communication. We identify the requirements of future networks beyond minute KPIs and use cases in Section III. Then, in Section IV, we introduce the architectural concept of organic networks. We present a high level architecture for organic networks in Section V. Finally, in Section VI, we summarize and conclude the article.

II. BACKGROUND

The recent publications from several industry and research organizations, and early beyond 5G/6G projects have provided an outlook into the potential of the mobile communications systems of 2030. Many of them showed a tendency to focus on use cases and KPIs. While these are important and provide a good starting point, the focus on KPIs during 5G development did not yield the results hoped for, and the solutions needed to support them are yet to be identified. So far, the most significant use cases, for example, in the Internet and mobile networks, only emerged after the new technology was already developed and deployed. We propose instead to orient the development along the technological requirements anticipated for the networks of 2030. Once these are established, we can identify potential approaches to support them.

When it comes to approaches, we perceive a significant gap between the telecommunications industry and the broader IT community. While modern hyperscalers take advantage of virtualization for flexibility and abstraction to serve their global user base, mobile network standards still do not leverage the full potential of the technological advances of the past decade(s). Even though the SBA approach appeared to be a step in the right direction, in the end, it will not be able to cope with future requirements. It suffers from high complexity [1], employs protocols that are optimized for past limitations of communication capabilities and is not adapted to the new ones [2]–[4].

A. RELATED WORK

By now, a large number of publications has tackled the use cases of the 6G networks, steering the discussions towards specific visionary applications [5]–[11]. Indeed, based on these use cases, another set of publications aimed to define the KPIs that the new 6G technology will have to reach to support them. They span from the typical increased capacity and lower delay communication, to reduced energy consumption, improved sustainability as well as high impact economical and societal goals [12]–[14]. Other studies are concentrating on the development of specific technology areas in isolation, proposing significantly biased architecture models towards some specific domains, however, disregarding the impact on others [15]–[18].

Uusitalo et al. outline the perspective of the European 6G flagship project Hexa-X, involving both European academia and industry partners [19]. Their vision presents new use cases and technologies. While 5G focused on performance and industrial applicability, 6G expands this view and also considers aspects, such as environmental, economic, and social sustainability. The organic network architecture we propose is aligned with the architectural principles [20], [21]. The high-level KPIs they identified include Network Flexibility, Separation of concerns of Network Functions (NFs) and ease of adding new functions [14]. They state that "The 6G architecture must be more flexible to accommodate new types of end user devices and access network topologies which calls for dynamic functionality upgrades and function distribution to match changing deployment needs." [20]. Our proposal aims to address these KPIs. Furthermore, [20] states that "another reason why a new architecture is necessary is the realization of the Continuum Orchestration concept." Continuum orchestration refers to the unification of the Management and Orchestration (MANO) of Core Network (CN), Radio Access Network (RAN), transport, and extreme edge. Discussing the RAN and core NFs, they propose a restructuring towards "independent NFs" [22]. The independent NFs concept aims to reduce the dependencies (or interfaces/ reference points) between CN NFs. It is in line with our core network service architecture proposed later on. With regard to Control Plane (CP) connectivity, they state that "the connectivity between the dispatched NFs instantiated in different clouds need to be set up in an efficient technology-agnostic manner" [21]. To address this issue, our proposal includes a zero-touch solution for dynamic CP connections.

In addition to the challenging goal of achieving the United Nations Sustainable Development Goals (SDGs), the Next Generation Mobile Networks (NGMN) Alliance demands global solutions in the areas of standardization, supply chain, and security [23]. Given increasing system complexity, they ask for end-to-end system automation, visibility, efficiency and management, implying improvements to automation including through AI, monitoring and telemetry as well as overall MANO. They see the trend towards network disaggregation as a challenge but also a driver of the digital transformation [24]. Problems with interoperability in multi-vendor systems are one of those challenges, which can be alleviated by reducing the number of NF interfaces.

Wei et al. identify further technological enhancements, especially for improving Radio Access Technologys (RATs) [25]. Here, mainly technologies that require new frequencies are mentioned. For instance, mmWave, THz communication, and Optical Wireless Communication (OWC) are considered as possible 6G technologies, with the latter including visible light, infrared (IR), and ultraviolet (UV) spectrum. For all technologies, both frequencies and bandwidths are steadily increasing due to the increasing demands on the data to be transmitted. Tataria et al. predict peak data rates of $\geq 1\,\text{Tbit/s}$ [10]. However, using higher frequencies, challenges such as line-of-sight (LOS) dependability, path loss, and hardware availability arise. This results in the necessity of novel air interfaces. In addition, Tataria et al. agree that new frequencies and improved RATs are the basis for meeting the stringent requirements of emerging 6G use cases [10]. Moreover, to further improve Quality of Service (QoS), such as latency, not only the front-end but also the back-end needs to be improved. Therefore, they propose replacing the dedicated transport networks with fully virtualized network slices on top of the existing Internet infrastructure, using Software Defined Networking (SDN). They postulate that a "flattening or significant reduction of the architecture is necessary to comply with 6G use case requirements". [10] Following this idea, a core-less cellular system is possible. This leads to a more and more distributed system. Consequently, network programmability is needed [5], [26], while the network composition can be supported by ML and AI algorithms. Indeed, the capabilities of ML and AI are highlighted in most 6G visions, such as those from 5G Americas [27] and 5G Infrastructure Public Private Partnership (5GPPP) [13]. Due to the continuing increase in system complexity, advanced network management approaches such as zero-touch management need to be taken into account when considering the network architecture as a whole [28]. Solutions such as the specifications of European Telecommunications Standards Institute (ETSI) Experiential Networked Intelligence (ENI) [29], Zero-touch network and Service Management (ZSM) [30], and Generic Autonomic Network Architecture (GANA) [31] are examples of existing frameworks. But they are external systems integrating management interfaces, rather than part of a holistic end-to-end design approach.

Krummacker et al. present a dynamic architecture that is able to manage, provide, and interconnect available contexts [32]. The abstract architecture leads to increased interoperability between IT systems, which are more and more relevant for mobile communication systems. Especially when implementing organic networks, this framework can support the organic growth of a system.

Of particular importance is also the required flexibility of 6G network functions. In an organic network, not only the growth is important but also the mobility of its network functions. Thus, a network function may be relocated for a variety of reasons. These may include device mobility, energy consumption, maintenance, and reconfiguration. Therefore, both challenges and a solution space for live migration of key 5G core network functions were investigated [33].

Even though context management and mobility of network and application functions are among the most important requirements for realizing an organic network, other features have to be considered as well. Therefore, a concept for realizing an organic network paradigm for both existing 5G and upcoming 6G technologies was proposed [34]. In this article, we update and extend this proposal, to provide one of the key building blocks of our holistic network architecture.

B. USE CASES

In this section, we present a set of potential 6G use cases, in order to prepare the mind of the reader with a realistic vision, providing a close-to-reality description that further motivates the proposed architectural vision and key technologies.

At the moment, there is a growing demand for more flexible mobile network setups that are able to react to changing circumstances. This leads to a continuous, agile adaptation to changing load or service requirements taking available infrastructure resources into account. This use case orientation is doubled by the wider adoption of private networks, designed for very heterogeneous applications. Therefore, we expect that the static infrastructures of 5G will be extended towards a highly mobile and distributed infrastructure, potentially using third party links. Based on these new directions, we classify the use cases based on two new axes: network mobility and coverage area, as illustrated in Figure 1.

We have selected the following use cases to cover a good variety of potential new fields for future organic 6G networks. Today, the areas listed below could not be supported sufficiently by 5G networks, due to missing functionalities, especially in the field of self-deploying, nomadic, or highly distributed mobile networks.

1) Distributed manufacturing: in order to optimize the production chain including the manufacturing itself as well as the management and maintenance of the distributed factory facilities, there is a need for a new sort of network, highly distributed while at the same time having only local coverage at the specific locations, which cannot be provided by today's private 5G networks.
2) Logistics: one of the key use cases for maintaining the efficient worldwide goods exchanges market, defined by a wide range of mobility (e.g., warehouses, trucks, trains, maritime), and density (e.g., warehouses, harbors, container depots, or vehicles) as well as of a very wide number of users and administrators. Here, a new 6G standard can provide possible solutions, which are not addressed in 5G, like hand-over processes between different operators, and trustable data exchange.
3) Public Events: require the deployment of temporary high density networks in either dense urban or remote areas, mostly to respond to the communication needs of subscribers, but also of security, event logistics or rapid responders. Which is in principle already possible with the 5G standard, but not all problems regarding the mentioned use cases are solved. This includes new concepts for underlay networks and safety critical events.
4) Agriculture: Seasonal shifting leads to fast changing demands on a network with regard to the tasks that have to be fulfilled and the geographical area involved. For operators of private agricultural networks, it would not be feasible, considering cost, resource and energy consumption, for their networks to cover all fields at once. As a new concept of 6G, an organic structure moving to collect data and transmit commands to different connected devices promises to be a more suitable solution.
5) Construction sites: Depending on each task, the setup of networks owned by an operator can look totally different. What can a fast-changeable and organically changing infrastructure look like? On a construction site, the surrounding situation might change within a day. Therefore, a network must be able to deal with these new situations, preferably by itself. As the operators of private networks are not experts in mobile communications, the organic network must bring AI features to be able to fulfill changing demands by automatically adapting mobile networks. In the best case, this works with a zero-touch solution – functionality, which is also not covered by 5G as of today.
6) Public Protection and Disaster Relief (PPDR): Networks administrated by emergency services like disaster relief or firefighting need to be deployed quickly, in different size and capacity, spanning from a single ambulance to a wide area network, at specific incident sites, for a limited time as either separate or operator integrated networks. A possible solution to fulfill the demands of this use case could, e.g., be a combination of zero-touch and organic networks, which is so far not covered by 5G either.

C. EXISTING NETWORK CONCEPTS AND THEIR LIMITATIONS

The classic network architecture concept was focused on the optimization of the message exchanges and their processing in the network. Spanning from 2G up to 5G, the network architecture was dominated by the limited compute and communication technologies able to support the communication, especially by the radio link capacity. Because of that, it concentrated on the development of optimized protocols, designed to be exchanged between dedicated physical components, spread across the network to meet specific latency requirements. In the meantime, with each new generation, due to the gradual increase of the infrastructure capacity, the functionality got polarized between base station and

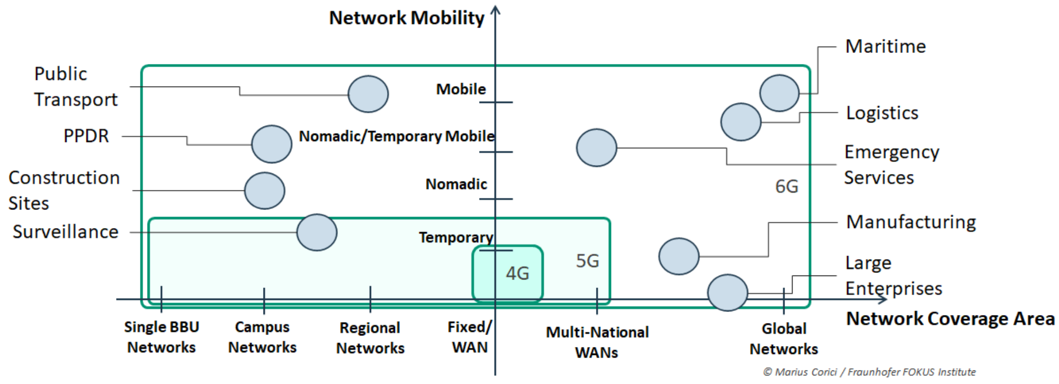


FIGURE 1: Relationship between use case, network class, and mobile network generation

central core networks where a large number of physical network functions were placed. Thus, the bottleneck moved from the access network to the transport connections. Due to this bottleneck and due to the stringent delay requirements, functionality has to move back to the edge.

With the development of high-performance data centers, a natural immediate step was the porting of the functionality from these physical network functions towards software components, starting with advanced 4G networks. This virtualization was done with two different perspectives: Network Function Virtualization (NFV) where an additional Orchestrator functionality was added to be able to dynamically deploy and scale fully virtualized networks and SDN where data path components, be them physical or virtualized, became controlled by software controllers.

As was to be expected, the porting of the software from the physical components to the virtual environment did not automatically provide the desired performance and flexibility gains. The reason being, that whenever an architecture is ported to a new environment, it remains the same architecture only in an environment for which it was not actually designed. To alleviate this, an SBA was adopted for 5G networks. In the SBA each of the previous network functions is implemented as one or multiple web services interconnected through dedicated APIs. Following the concept of micro-services [35], better aligned the 5G system with the trends of cloud native infrastructures. However, based on the concept of NFs, an over-reliance on horizontal interfaces and service internal states lead to a kind of ultra-complexity. Therefore, the SBA cannot achieve the scalability that micro-services enable. With this in mind, let us consider the technological requirements of future mobile networks.

D. TECHNOLOGICAL PREMISES

Current and future technological advances shape a new environment and new possibilities for 6G networks. From the physical layer's new RAN technologies all the way to the management and orchestration layer, new developments have the potential to dramatically alter the core network architecture and the way it operates. This section introduces the key technological premises impacting organic networks.

1) Higher capacity in the RAN than in the transport

Radio technologies spanning multiple orders of magnitudes of frequencies, the adoption of micro-, nano- and femto-cells, massive Multiple Input Multiple Output (MIMO) and the explosion of available end devices, mean the capacity and traffic of the RAN will exceed that of the transport network. To avoid bottlenecks the core network needs to be able to take advantage of localized services, extending the existing trend of Multi-Access Edge Computing (MEC) towards dynamic localization, re-location, and migration.

2) Deployment matters

Communication networks will no longer be deployed only as monolithic national systems. Instead, different types of deployments, such as local private networks, will emerge and change what a network can be. Adaptability to different deployment scenarios will be a key feature of 6G networks.

3) Compute everywhere

Smart devices and mobile edge computing offer new opportunities for the exploitation of available computational resources. The future core network will have to take advantage of the end-to-end computing capabilities of the infrastructure and extend itself from central offices across the network and all the way to the edge, RAN and even User Equipment (UE), to provide the most resource efficient, localized services.

4) Data everywhere

A myriad of devices will be spread throughout the environments humans build and occupy. Those devices will produce unprecedented amounts of data that can be collected and analyzed. Besides influencing network management and operation, this data will play an essential role in many use cases and influence the real world.

5) Control everywhere

The complexity and diversity of future communications networks necessitate abandoning purely centralized control approaches. Core functions and services will be distributed across various sites such as data centers and networks. Segments of the network will have to morph(/adapt/change/reorganize) according to local requirements and challenges with no or only little oversight or input from central offices. To ensure the robustness, resilience, scalability, and performance of the control plane, appropriately scoped, self-organizing control entities have to be deployed dynamically and automatically across these networks. This requires the existence of a resilient control plane fabric that provides control plane connectivity among all networked resources, including the control entities. Recent developments in the area of autonomic management [36] may serve as a basis.

6) New software development techniques

The softwarization of core networks, which already started in 4G and was explicitly addressed by the 3rd Generation Partnership Project (3GPP) with the SBA, will continue on the path to 6G. Softwarization intrinsically requires the adoption of state-of-the-art software development techniques. Here, core network developers can learn from the cloud native hyperscalers, who employ continuous integration and development techniques to rapidly update, test, and deploy their software. A cloud native core network has to follow suit, if it wants to adapt to its environment and user demands.

7) AI everywhere

Artificial intelligence is being developed to address more and more use cases and allows automating tasks, which traditional computing approaches struggle to cope with. Efforts to integrate AI into network analysis and management are already ongoing and expected to bear fruit in 6G networks. However, 6G AI can go even further and will enable advanced network customization through zero-touch deployment, operations, and maintenance.

8) Growing Security and Reliability Challenges

The beginnings of computer networking and wireless mobile networks enjoyed the luxury of a friendly, green field environment, where participants were collaborating without ulterior motives. The continued expansion of these communication technologies over the decades has seen the involvement of many different parties of various economic and political motivations. As more and more critical infrastructure joins the global information networks and in the light of continued threats to the peaceful operation of the Internet, security, trustworthiness, and resilience of technologies become ever more critical to their success.

III. KEY TECHNOLOGY REQUIREMENTS AND APPROACHES

Continued progress towards all-encompassing global wireless communication networks connecting everything everywhere in the most efficient possible way poses new requirements on all components from the RAN to the core network and network management. Flexibility in scale, function, and location are at the core of these requirements.

A. SUPPORT OF CORE NETWORK FUNCTIONALITY

The 6G core network will have to continue supporting the key network services of previous generations. This includes at least the 5G network services – authentication and authorization, mobility and session management, reachability of idle devices, charging and lawful interception, narrowband control plane-based communication, multicast – as well as beyond 5G and new services such as network positioning and sensing or ultra-reliable and low-latency signaling.

While the advances in connectivity do not change the basic network functionality itself – enabling the exchange of data by connected devices, a significant change to be considered is the dynamicity of core network deployment. Although software-based, the current 5G network architecture is handling resources in a very static manner. With 6G, we expect that compute resources would be available in multiple network locations. As such, the network could automatically deploy itself on top of these highly dynamic resource pools as shown in Figure 2. To be able to benefit from this characteristic in a fluid manner, a new set of control plane functionality, which gains knowledge of both the service requirements and of the infrastructure availability and automatically changes the network deployment, needs to be developed. For this to function, the network functionality should have enough degrees of freedom, which is currently not the case.

B. INTEGRATION OF BACKHAUL/TRANSPORT

With the deployment of very high-capacity access networks within 5G, the bottleneck shifted from the access to the transport network. The current assumption that the transport network is well dimensioned and planned to handle the RAN data traffic has to be rethought in this context. Furthermore, new directions like self-backhauling, radio-strips, and the convergence with NTNs provide dynamicity to the transport, which has to be accounted for. The challenges of backhaul diversity are indicated in Figure 2.

Specifically, when reserving resources on the end-to-end data path, the reservation should concentrate not

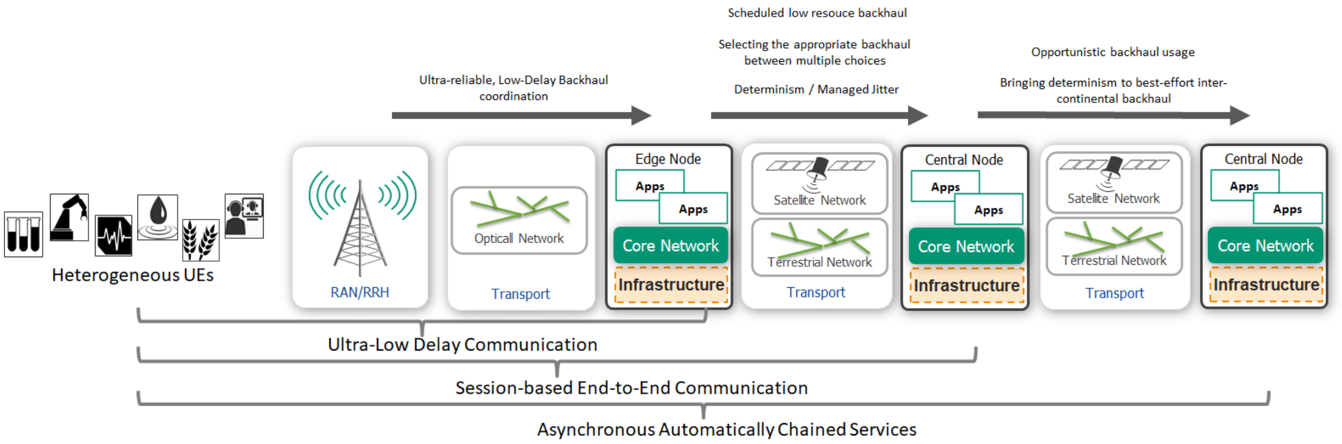


FIGURE 2: Core NF placement in different locations with diverse backhauls

only on the access but also on the transport selection: Which transport network to use at a specific location, given multiple options? The specific characteristics of the transport links (e.g., capacity, delay, jitter) have to be taken into account. Hence, the control plane should be extended with cross-layer functionality to understand the lower transport layer options and momentary characteristics and to execute the control in both directions.

C. SIMPLIFIED AND RESILIENT CONTROLLABILITY OF ALL RESOURCES

A network infrastructure that provides organic growth and elasticity requires a corresponding control plane fabric (see Figure 3) that expands and shrinks with the networked infrastructure resources. So as soon as a new resource (physical or virtual) is instantiated and connected to the network infrastructure, it should become automatically controllable for Operations, Administration, and Maintenance (OAM). We envision a unified control plane fabric that interconnects all resources for control plane access in a self-organizing and zero-touch manner. Here, "Zero-touch" means without any manual configuration or administration. Today's network resources usually have a separate out-of-band OAM interface that allows for control plane access by network operators using a dedicated OAM network. However, this separate, dedicated network must be adapted to the dynamically changing infrastructure as well and also requires its own setup and management, e.g., assignment of IP addresses, subnets, and so on. This prohibits very fast scaling and also "infrastructure free" approaches, as well as the use of adaptive infrastructures that may change quickly.

A self-organized and scalable control plane fabric is the foundation for (network) resource controllability as well as largely using "in-band" control, which uses the existing data links of the infrastructure instead of requiring a separate out-of-band control network. In-band control, however, requires mechanisms that provide a higher forwarding priority for control traffic. The envisioned approach is to interconnect all resources in a unified control plane [37] by employing a zero-config and zero-touch routing protocol that is able to operate across a mixture of sparse and denser topologies, such as data center fabrics. The network infrastructure can, thus, grow or shrink as required or even be split: the control plane fabric should sustain controllability over all reachable network resources. An ID-based addressing would help to get access to resources that move in the underlying infrastructure such as Virtual Machines (VMs) or UEs. Control plane applications like SDN controllers, NFV controllers, or 6G core applications may run on top of this.

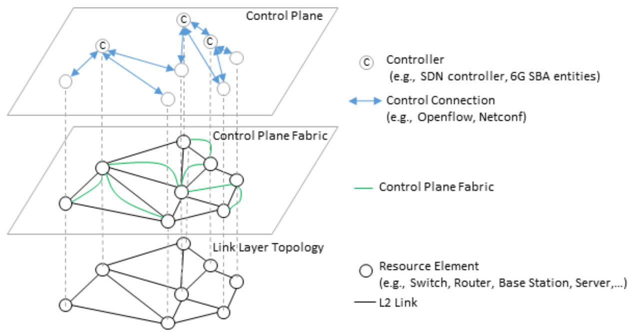


FIGURE 3: Self organized, scalable control plane fabric

D. COMPLEXITY REDUCTION

To provide a good user experience and enable efficient operation, mobile networks need to maintain a streamlined architecture and avoid unnecessary complexity. High complexity results in increased response latency and lowered Quality of Experience (QoE). As explained in Section II-C, previous approaches suffer from high complexity. In particular, the network function concept has shown its limitations in regard to scalability and efficiency [1]. We propose regrouping functionality beyond the NF concept to streamline procedures and reduce complexity and overhead. One way to reduce overhead in the control plane would be to minimize horizontal communication.

E. ORGANIC GROWTH

The Organic Network needs to be able to grow from a single or very few nodes to a large geographically distributed system of central clusters and edge nodes (and shrink back) over (possibly short amounts of) time. Figure 4 provides an abstract representation of the organic growing and shrinking of a network. The more diverse the components comprising such a system are, the more dimensions it can be scaled against and the more decisions about growth have to be taken. Therefore, growing a highly heterogeneous system is complex and difficult to automate.

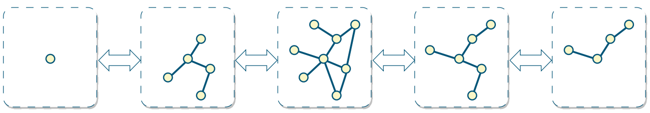


FIGURE 4: Organically growing network

We propose creating a more homogeneous system, in which a few key entities are capable of handling the majority or all types of requests by themselves. Such a system can grow easily and without the need to make complex placement decisions. To homogenize the core network, one has to move past the notion of distributed NFs communicating through interfaces. Instead, we suggest replaceable processing entities composed of dynamically invocable routines as the building blocks of the network.

F. VERY FAST SCALING

Telecommunication networks need to be able to handle different amounts of traffic in different locations at different times. One of the biggest problems has always been handling a relatively sudden surge of traffic in a given location over a shorter period of time. To handle such bursts of traffic, networks were commonly over-provisioned. This inadvertently led to resource inefficiency and underused infrastructure. Efforts taking advantage of resource optimization and virtualization to address the issue have been ongoing and 5G networks now incorporate such approaches to an extent. In the future, the expected peak traffic volume will become even larger, while increased attention has to be given to energy efficiency. Therefore, 6G core networks need to further improve their ability to handle the changing traffic demands in the most efficient way. It can only be achieved with a high degree of very fast scalability. The virtualization of the core network functions has brought some scalability, but without a clean separation of state and processing, it cannot reach its full potential. Therefore, the Virtual Network Functions (VNFs) should be stateless by design, if possible.

Another problem for core network scalability, is the UE facing front-end, i.e., the interface towards a connected end device. The more requests have to be exchanged with the UE, the more the UE has to be served by a particular NF instance. This limits the ability of the UE to be served by multiple NF instances and, therefore, the scalability of the core network. The front-end has to be stream-lined and scalable.

G. INCORPORATION OF THE ADAPTIVE INFRASTRUCTURE

Our current networks are fairly static, despite the underlying architectures often enabling a reasonable amount of adaptation. Examples include the reconfiguration abilities of an optical network, where lightpaths can be changed to improve latency between locations of service execution. Another example could be drones extending a RAN on-demand to provide capacity and coverage where needed. The key goal would be to integrate the network adaptation and the service overlay adaptation into a coherent picture.

In order to realize highly flexible, dynamic and adaptive scenarios, stateful services may also have to change their locations. Possible reasons for this are mobility support, resilience and self-healing concepts, QoS optimization, as well as improved efficiency. Further, seamless reconfiguration of services is a possible requirement. Therefore, it is necessary that previous protocols and processes of more or less inflexible and static systems are expanded by an overarching component. This component should ensure communication across networks and infrastructures.

Thus, existing live migration approaches as well as state management approaches that are under investigation in the IT domain could provide the required flexibility. As there are several metrics that can be minimized, such as service downtime, migration time, transmitted data volume, resource load, and energy consumption, the most appropriate approach has to be selected and possibly adopted. Moreover, a trade-off between non-invasive and invasive live migration concepts has to be considered. Here, a careful consideration must be made between required performance and transparency, whereas full transparency leads to lower performance and vice versa.

H. HIGH PARALLELIZATION CAPACITY

Beyond 5G the number of connected devices and amount of data traffic are expected to continue to increase. To handle the rapidly increasing data traffic in 6G, more parallel capacity is needed. Therefore, 6G functions need to be distributed to ensure the best network stability and performance. In order to achieve this, data processing

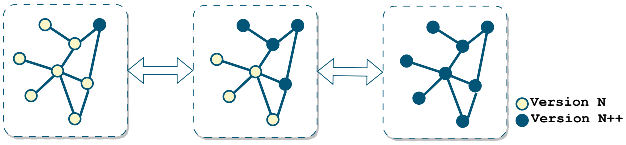


FIGURE 5: Introducing new functionality: Migrating network nodes to a new version

must be brought closer to the customer. Here, edge computing has an important role to play by providing cloud computing functions not only in the RAN but also in the core network. However, the challenge in this case is to keep the subscriber state consistent at all times as different edge nodes handle requests from the same subscriber. VNFs will need to be disassociated from the subscriber state they process. Synchronization and access control mechanisms need to be enforced across the network. In addition to the synchronization problem, the parallelized edge nodes also need an effective load balancing. While load balancing is not a new problem, a viable solution will be highly dependent on the kinds of VNFs, protocols, interfaces, and traffic patterns encountered.

I. SIMPLIFYING THE INTRODUCTION OF NEW FUNCTIONALITY

To grow and evolve the network organically, it should be possible to change functionality dynamically. One major hindrance to the introduction of new functionality into the network are the numerous interfaces between components. To provide a service, multiple components have to interact. If a new function is to be introduced, or an existing one changed, multiple components and their interfaces will be affected, leading to a cascade of alterations in the network. This kind of complex alteration is difficult to execute on a running network without disruption. If, instead of components dedicated to a specific functionality, the network comprises independent, interchangeable workers, new functionality can be introduced one by one and without interrupting the overall operation. Figure 5 presents a step-by-step migration of network nodes from one version of the software to the next. If workers are to be independent, their direct interactions need to be minimized. Ideally, any functionality could be provided to a UE by a single worker on its own. There are two challenges to this worker-based approach. First, each worker needs to be able to provide all possibly required functionality. Second, all workers have to be stateless, and the subscriber state has to be available and synchronized globally.

J. SUPPORT FOR NEW, AGILE & FLEXIBLE DEVELOPMENT & DEPLOYMENT

In recent years, the Continuous Integration & Delivery (CI/CD) approach emerged as a paradigm of agile software development of cloud-based (native) services and applications. Based on the softwarization and virtualization of functions, telecommunication networks can leverage these and similar DevOps [38] techniques to create a more adaptable and dependable infrastructure. The 6G architecture and its inherent complexity present more challenges for the testing and integration of new functionalities. Evaluation of the correctness in varying state transitions given the dynamics in such systems is still an open research question. Therefore, suitable testing and fall back mechanisms have to be established, in order to handle unforeseen conditions and avoid dead-ends in the release life-cycle. Canary releases will enable live testing of new functions in production environments [39], [40]. Moreover, in critical systems, the need for continuous simulation of the entire system can be required to represent the whole dynamic. The advantage of a continuous simulation is that disruptive testing mechanisms can be applied without risking errors in the real system. Chaos engineering, for example, can help identify issues, regressions, and vulnerabilities regular testing approaches do not cover [41].

K. NETWORK MANAGEMENT SIMPLIFICATION

Future communications networks are bound to be highly complex, distributed systems. The management of these networks by human operators will be exceedingly difficult. Tools for automation and monitoring will continue to play an essential part in network management. Current technologies will have to evolve to simplify the management and enable efficient operation. For example, the stream-lining of functional entities such as core NFs can alleviate management challenges, such as placement, scaling, and scheduling. Monitoring solutions need to be highly customizable in the types of data they collect and at which frequency. The configuration of which has to be exposed in a well-defined Application Programming Interface (API). For improved observability and decision making, the network needs to collect and aggregate telemetry data and make it available to (AI-based) network management entities and/or operators. It should in effect maintain a digital twin of itself.

L. ALWAYS RELIABILITY

As critical infrastructure, telecommunication networks have high reliability demands. If 6G networks are to replace their predecessors, they need to provide the highest possible degree of reliability. The reliability will have to go beyond the traditional five nines, by always remaining operational even when parts of the network fail. Partial network failures, backhaul interruptions, and other problems should not affect local connectivity and services. The network needs to be self-healing and able to establish alternative links. Here, the increased distribution of intelligence, edge computing, diversification of transport network technologies, and a robust control plane fabric will pave the way towards always reliable networks.

M. FLEXIBLE SECURITY

Providing a dependable communications infrastructure requires securing the interfaces between its components. NFs, infrastructure, and UEs need strong, flexible, and secure authentication and authorization. With the high dynamicity of future networks, a new security overlay based on self-authentication and zero trust is needed. The security and privacy challenges of deep AI integration into the network need to addressed. Furthermore, post-quantum security algorithms need to be identified and implemented in a modular and replaceable way.

N. SUPPORTING OPEN AND DISAGGREGATED RANs

Historically, the RAN implementations were provided as proprietary solutions by a single vendor. In a drive towards more openness and competition in 5G RAN, companies have formed the O-RAN Alliance,[1] which proposes and specifies a new disaggregated architecture called Open Radio Access Network (Open RAN). Future 6G networks have to take advantage of the kind of functional splits of the RAN stack, building on concepts such as Open RAN. The Open RAN architecture includes near real-time and real-time RAN Intelligent Controllers (RICs) that represent control loops of different immediacy. Following the trend of MEC, core functionalities are being moved closer to or directly next to the RAN components, such as the Open RAN central unit and RICs. To avoid duplicating session and mobility management functionality in the RAN CP and edge core, these functionalities should be merged, and the respective core services should be extended by xApps. An xApp is a piece of software executed on the near real-time RIC in the Open RAN architecture [42].

O. RECONFIGURABLE RAN AND ADAPTIVITY

Flexibility and adaptability of future cellular systems have for a long time been recognized as key steps towards faster innovation cycles and expansion towards new use cases. 5G deployments in particular leverage virtualized RAN (vRAN) as implementation choice, to enhance flexibility at the price of energy consumption. A plethora of research works studying machine learning applications to communication systems design have recently emerged. In particular, deep learning (DL) has recently shown great potential for becoming a powerful tool to design, optimize, adapt, and secure wireless communications. With respect to implemented architectures, works either focus on substituting individual functions in the transceiver chains, or more progressively substituting larger blocks, primarily in the physical layer. Potential solutions could be based on end-to–end approaches, flexible reconfigurable higher layers or AI-Native RAN. For a softwarized, AI-native RAN to be efficient and flexible, there is a need for a software architecture where AI-native functions are "first class citizens", as opposed to VMs and containers. The architecture should match the data-centric abstraction of computing that neural processing provides, e.g., agnostic to instruction sets and memory hierarchies, which facilitates code reuse, portability, and hardware maintenance. Furthermore, it should support fine-grained provisioning of resources, based on fine-grained compute actions without the need to allocate compute and network resources for long time periods (e.g., hours, days)

P. HARDWARE ACCELERATION

With Open RAN and the ongoing development of the concept towards 6G networks, RANs transform from highly configurable to programmable systems. Following this trend, static provisioning of resources is no longer possible. The hardware deployed at the RAN is no longer a fixed-function device, implementing a given 3GPP release but provides APIs to attach applications with unknown compute demands. However, in contrast to similar trends in the core network, well-known concepts from NFV and cloud computing cannot be applied directly. The compute and latency requirements of the Physical (PHY) and Medium Access Control (MAC) layers mandate tight integration with accelerators like Field-Programmable Gate Array (FPGA)s and Graphics Processing Units (GPUs)/Tensor Processing Units (TPUs). With demand-driven, dynamic provisioning of Digital Signal Processing (DSP) functionality and control-loops, RAN implementations compete for finite compute resources and access to accelerators.

On a more abstract layer, one could regard these processes to morph, adapting to their environment to make full use of the available compute resources. There are many possibilities how this concept could be reflected on a more technical level. A PHY implementation could migrate from the GPU to the FPGA to reduce latency and jitter; an FPGA implementation could use more on-chip Random Access Memory (RAM) for caches and faster look-ups, or it could switch to using hard Forward Error Correction (FEC) blocks to support higher throughput; an AI/ML real-time control loop could use more complex networks for inference, if enough resources are available, or it could consider more input metrics or increase their fidelity and update rates to improve the decision-making process.

To realize these concepts, there are two central challenges that have to be addressed: First, it requires suitable APIs and abstractions that decouple implementations from the underlying hardware. Second, it requires scalable implementations that can morph to use resources opportunistically.

[1]O-RAN Alliance https://www.o-ran.org/

Q. SUPPORT OF NEW RAN FUNCTIONALITY IN THE CORE

From a core network perspective, three major directions in RAN development are significant: the spectrum shift towards higher frequencies, the mobile and nomadic deployment of the radio infrastructure, and the increased involvement of the UE in RAN decisions. The RAN in higher frequencies, such as sub-THz and THz, is expected to have reduced coverage, which implies that the connectivity would not be available for devices moving at higher speeds, and may be lost quickly. To maintain service continuity, the handover and parallel usage mechanisms should be re-thought. Furthermore, usage of new access technologies is highly dependent on the momentary device profile, including information such as speed, location and communication requirements.

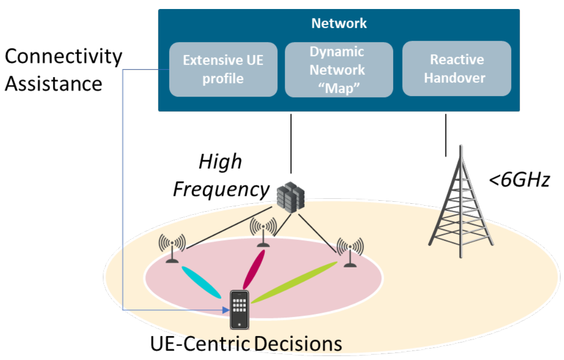


FIGURE 6: New RAN Functionality

Figure 6 gives an overview of the new RAN functionality. With the inclusion of mobile and nomadic RANs, the topology of the access will change dynamically. For the core network, this implies that the communication paths established may change, not only because of handovers of connected devices, but also because of the handovers of the base stations to other connectivity points in the network. Furthermore, this requires the development of a dynamic network map including the momentary accesses at a given location, as well as the momentarily allocated frequencies. By pushing more of the decisions from the radio side to the UE, the network changes its role from managing the resources to reacting to the UE decisions, executing the specific access control decisions after the connectivity decisions of the UE. To be able to guide the UE towards the decisions which are most likely to be accepted by the network, a new indication mechanism through which the network assists the UE with network connectivity discovery information and connectivity policies has to be developed.

R. UE-CORE EXTENSION & COOPERATION

The processing power of UE has seen steady improvements over recent years, beyond multi-core processors and gigabytes of memory. For 6G networks one can assume a large portion of end devices being capable of significant computational output. Such capabilities enable the UE to cooperate with the RAN and core network. Furthermore, the UE holds valuable information about the state of the RAN and itself. So far, this information has not been accessed by the core network. It stands to reason, that the network could benefit from more cooperative UEs. As long as the network can remain in control and enforce appropriate policies, to prevent exploitation by rogue UEs, there is a lot to gain. It might even be possible for UEs to execute core network functions themselves to process their own requests or those of other UEs.

S. SENSING/SELF-AWARE NETWORK

In 6G, sensing becomes a key capability of a network as such. The network acts as a sensor in two different ways: first, a continuous self-control/tracking, which creates a kind of self-awareness about the system state and second, an awareness of the geometry of the local environment created by Joint Communication and Sensing (JCAS). These new functionalities create a huge amount of traffic on top of the communication data flow. In order to minimize this the overhead, as much as possible of the data processing should be implemented locally on RAN device level. Unfortunately, this approach is limited by the computational resources of devices, and only allows for relatively simple algorithms that can provide only a rough estimate of the system state. For an in-depth and more importantly, joint evaluation of the sensor data, a pre-processed and compressed data set needs to be transmitted to a higher entity such as the core with sufficient resources for the data analysis.

The combined sensing data of all (mobile) network nodes/RAN devices is jointly processed using analytical, statistical, and AI methods to create a most comprehensive picture of the network state and the local environment, i.e., a digital twin. This digital duplicate of the network is employed to decide about actions to further optimize the functionality and state of the network, i.e., for an organic adaptation of the network to the momentary requirements.

The traffic created by the processing of the sensing information and the resulting signalling for an adaptation reaction correspond to a second network or "a network within the network" using the same hardware but with different optimization priorities. Nevertheless, both networks have to be optimized jointly, since they are based on the same hardware. This refers especially to time-critical orders or safety and security relevant sensing information and reaction to commands versus high priority communication data that requires low latency.

Thus, the management/orchestration of a "network as a sensor" calls for new approaches or further development of already existing algorithms dealing specifically with JCAS. Also, the trade-off between the cost of computational effort versus the benefits of an optimal solution have to be considered.

T. INTEGRATION OF MULTIPLE NETWORKS

By talking about new functionalities in 6G an increasing demand for a flexible network structure arises, not only for classical Mobile Network Operator (MNO)s, but also regarding private campus networks, which have already been introduced with 4G & 5G and must now be adapted, in order to meet new demands and concepts in 6G.

Aspects like nomadic, underlay, or organic networks are very promising features for deploying private 6G campus networks for private operators and companies. Many functionalities like infrastructure free and organically growing networks have been described above and are also very suitable aspects in the context of private networks, where the demands of operators differ from those of classical MNOs. Reduced complexity or a simplification of network management are key functionalities which need to be integrated in 6G, so the integration of private 6G networks gets more attractive for potential operators regarding aspects of costs and maintenance effort.

However, by integrating described functionalities in private 6G networks new challenges arise. So far, mobile communication standards like 5G do not feature any concepts for core-to-core communication, which is quite an important aspect for the integration of multiple networks into a big overall infrastructure. Thus, it is necessary to find concepts and solutions for upcoming challenges in respect to enabled core-to-core communication. What comes to mind first is that with radio resource sharing inside a mobile communication network with two or more cores operated by at least two different parties, additional problems in the area of security and trustworthiness of data arise. First approaches of how solutions could look like are proposed in [43].

Beside the already introduced challenges in the field of trustworthy data, additional requirements need to be fulfilled, in order to enable organic 6G networks in the context of non-stationary or roaming mobile communication networks. So it is necessary, that an efficient radio resource management is established, which is dedicated to every participant inside an organic overall infrastructure. This management plane should be able to control evolving features of 6G, especially regarding topics described in this subsection. By realizing the integration of multiple networks, the aspect of licensing of operators in networks emerges. A solution for the enforcement of resource allocation among organic network participants needs to be found. This issue could also be taken over by the radio resource management under the aspect of trustworthiness of data and the usage of distributed ledger technology.

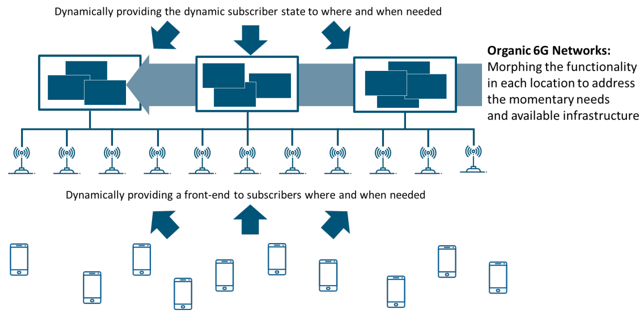


FIGURE 7: Organic 6G Networks Concept

U. SHAPING THE NETWORK TO SPECIFIC USE CASES

As presented in Section II-B and Section II-A, in 5G and even more so in 6G, telecommunications networks will support more and more diverse use cases. Each use case can have different functional, KPI and Key Value Indicator (KVI) requirements. To accommodate these, the network will have to adapt in size and functionality. However, a network can only reshape itself dynamically, if it can sense the changing use cases. How can the changing use cases be recognized by the core network?

Deep packet inspection could be employed to detect use-case-specific protocols or some kind of tagging at a packet level similar to QoS Class Identifiers (QCIs), but this would require per packet/connection processing on the data plane and a feedback loop with the core network. Typical traffic patterns could be recognized by advanced traffic analysis with AI/ML assistance. Alternatively, end devices could request access to use-case-specific slices. This would need to be reflected in the front-end API and only works under the assumptions that devices have information on their slice requirements and that they can be trusted to report this truthfully. Otherwise, a zero trust approach will require continuous, automatic policing and checking.

Through configurability, use-case-specific grouping or classification of NFs, slicing, and virtualization the network can be shaped as needed. The management and orchestration layer needs to be able to execute the necessary customization.

IV. ORGANIC 6G NETWORKS: BRIDGING THE 15-YEAR-GAP BETWEEN IT AND TELECOMS

Organic networks are a software-centric architectural approach that enables the network to continuously morph its own shape and functionality to address the momentary, localized user- and application-specific needs within the available infrastructure resources. They enable a highly customized and ultra-flexible network, providing coherently and fluidly the best possible services to end devices, automatically adapted to the underlying, dynamic infrastructure. It pushes the mobile network concept further towards autonomous adaptive networking than the 5G SBA can, while allowing to adhere to the stringent service level requirements. Through automatic adaptation, it becomes resilient and dependable. Figure 7 illustrates the concept of Organic 6G Networks: mobile devices connected to the network via radio access are served by a dynamically changing network infrastructure. Let us consider the different aspects in more detail.

A. MORPHING

A special effect in motion pictures and animations that changes one image or shape into another through a seamless transition. Traditionally, such a depiction would be achieved through dissolving techniques on film. Transitioning through a metamorphosis to achieve the next state of being. A natural process that allows developing advanced capabilities. In the context of organic networks, it represents the gradual and subscriber non-perceivable evolution of the network functionality in a given network location.

B. MOMENTARY NEEDS

The service requirements of the connected devices, which change over time and location. With 6G, it is expected that more of the decision will be passed to the UE, making service establishment a collaborative process between UE and network.

C. INFRASTRUCTURE RESOURCES

The physical network devices (e.g., antennas, cables, servers, switches, user equipment, modems), which change dynamically over time and the virtualized abstraction layers built on top of them (e.g., SDN, Infrastructure as as Service (IaaS), Platform as as Service (PaaS), Network as as Service (NaaS)).

D. HIGHLY CUSTOMIZED

Modified to suit a particular individual or task, personalized. In our case, modified as much as possible to fit the user or application requirements, and the available infrastructure. Customization can be obtained through configuration, conglomerating, or disaggregating functionality, defining procedures (as data flows and processing elements) and redefining functionality.

E. FLEXIBLE

Easily modifiable to respond to the momentary needs and altered circumstances. Altering the network needs to be straightforward and fast. Implemented with clear and concise APIs and interfaces. As the infrastructure becomes more flexible, so does the network software running on top of it.

F. COHERENT

Forming a unified whole and having its parts related in an organized and reasonable way. It is certainly no uniform, but works together in an end-to-end consistent fashion across the distributed infrastructure. End-to-end as in subscriber end-to-end services and as well as deployment across the distributed infrastructure.

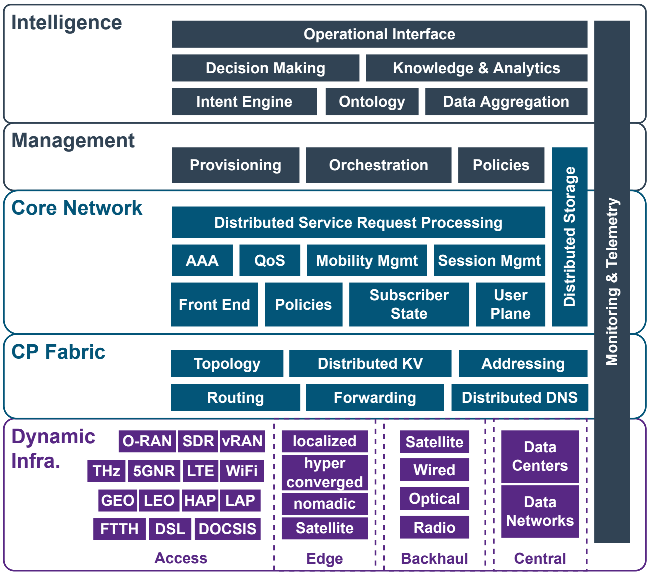


FIGURE 8: Organic 6G Network: High Level Architecture

G. FLUID

The network shapes itself along the infrastructure like a liquid. It flows around obstacles and disruptions, naturally finding alternative paths. It does not overflow easily, respecting a surface tension by spreading load evenly.

H. AUTOMATIC ADAPTATION

Automatic, autonomous, AI native network management and orchestration relieving the human administrator of most of her role during the decision making and execution of the morphing process. This enables fast redefinition of functionality by the network itself.

I. RESILIENT & DEPENDABLE

The network handles disruptions gracefully, whether in the infrastructure, service or management layers. Breakage of components, outages due to disasters or attacks hinder operation as little as possible. Fluctuations and sudden surges in load do not affect services significantly. The network can absorb, mitigate, and recover from attacks by external entities. Furthermore, it needs to analyze and learn from incidents to harden itself for the future.

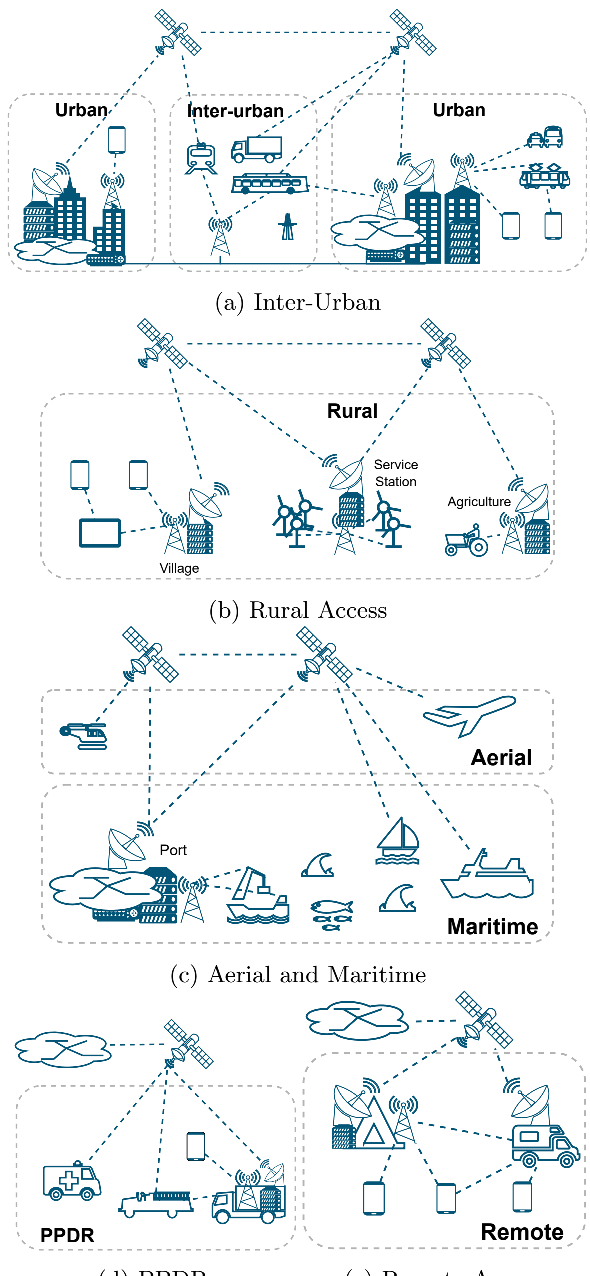
V. ORGANIC 6G NETWORKS: HIGH-LEVEL ARCHITECTURE

How can the organic networks approach be applied to mobile networks to fulfill the 6G vision? We propose the following abstract, high-level architecture for Organic 6G Networks, as shown in Figure 8. As the mobile network of the future, it will provide access and transport to a great variety of end devices. The diversity and dynamicity of the underlying infrastructure drive the organic architecture. A zero-conf control plane fabric takes care of CP traffic forwarding and routing by abstracting the underlying infrastructure. This fabric automatically adapts to dynamic changes in the infrastructure and provides seamless CP connectivity between all entities. Thus, it is not only fluid but also resilient due to its zero-conf design, because it cannot be broken by configuration mistakes. The organic core network enables end-to-end communication services and applications in a flexible manner. Monitoring is deeply integrated into all parts of the networks to obtain the required level of self-awareness. MANO allows the provisioning of the infrastructure and virtual network elements/functions. In the distributed intelligence plane, AI and ML analyze monitoring data to execute or inform decisions and enable the advanced control mechanism steering the network. We discuss these layers starting from the bottom with the infrastructure.

A. DYNAMIC INFRASTRUCTURES

Mobile network infrastructures will become a lot more complex in the future. Technologies such as NTN, drones, High Altitude Platform (HAP)s, Low Altitude Platform (LAP)s, Reconfigurable Intelligent Surface (RIS)/Intelligent Reflecting Surface (IRS), core-UE-collaboration, nomadic network segments, cell-free access, vRAN, Open RAN, Non-Public Networks (NPN), dynamic NF placement and infrastructure-less networks will introduce significant dynamicity to the system. The potential convergence with WiFi and fixed access such as Digital subscriber line (DSL), Data Over Cable Service Interface Specification (DOCSIS) or optical fiber (e.g., Fiber to the X (FTTX)) further increases complexity. Another factor increasing flexibility is the diversity of available underlying hardware capabilities, e.g., FPGAs, GPUs, TPUs, smart Network Interface Controllers (NICs) and potentially others. In the transport networks, front-, mid- and back-hauls will be provided not just by wires and fibers but also wirelessly and via satellites. The new x-hauls differ greatly in characteristics, such as jitter and continuity, challenging established assumptions about end-to-end connectivity.

An overview of some dynamic scenarios that 6G networks are facing is shown in Figure 9. While urban and rural use cases will remain central, they will become more dynamic by including nomadic nodes, such as trains and buses commuting between urban centers. The network will be extended further, using NTN. International land, air, and maritime traffic provide even more nomadic network segments that exist in areas difficult to cover with terrestrial networks. The vehicles differ greatly in speed and duration of movement. Airplanes traveling at high velocity and altitude remain particularly difficult to service. Temporary networks for PPDR with high priority requirements, will have to be supported by the existing infrastructure but also work with only limited or no backhaul connectivity.



(a) Inter-Urban

(b) Rural Access

(c) Aerial and Maritime

(d) PPDR (e) Remote Access

FIGURE 9: Dynamic Infrastructure Scenarios

Deep monitoring, joint communication and sensing as well as virtualization will allow advanced control of components at all layers. But the non-user data, which needs to be transmitted throughout the network to leverage these technologies, will require advanced control traffic scheduling, distributed processing, and local as well as regional aggregation. The architecture has to allow for this kind of dynamicity.

B. CONTROL PLANE FABRIC

A self-organized and scalable control plane fabric is the foundation for (network) resource controllability for organic CNs. It interconnects all resources in a unified control plane by employing a zero-config and zero-touch routing protocol (e.g., [44]) that is highly scalable and able to operate across a mixture of sparse and denser topologies, such as data center fabrics. The network infrastructure can thus grow or shrink as required or even be split: the control plane fabric sustains controllability over all network resources. An ID-based addressing helps to get access to resources that move in the underlying infrastructure. Control plane applications like SDN controllers, NFV controllers, or other core services applications as proposed in Section V-C run on top of this. The CP fabric can further serve the network by exposing its knowledge about the changing network topology. A built-in distributed key-value store provides a simple name resolution service and can also be used for service or resource discovery. Due to its tight integration with the routing protocol, it reduces the interdependence between components and contributes to architectural simplification.

C. CORE NETWORK

The CN takes care of crucial tasks, such as Authentication, Authorization and Accounting (AAA), mobility and session management, User Plane (UP) control, legal interception and QoS enforcement. In traditional networks these were centralized. As the number of UEs increases and latency as well as locality requirements get more stringent, future networks will have to handle service requests at locations spread more and more across the network. This can only be realized through a highly distributed system that processes the numerous service requests of the UEs in parallel.

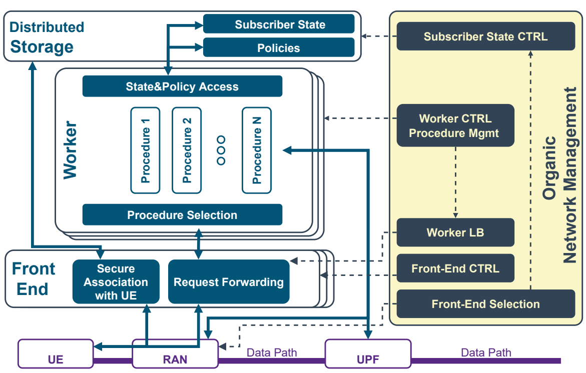


FIGURE 10: ON Core Services Architecture

The core network architecture needs to be restructured to better support the dynamic infrastructure [34]. The proposed organic core network service architecture is presented in Figure 10. A globally distributed storage substrate shares the synchronized subscriber state, policies, and configuration between nodes with a unified interface, accessible from all core network components. The core network functionality is provided by interchangeable, dynamic workers, which can adjust the services they support based on current application requirements. The workers do not store any state information about the subscriber. Instead, they perform atomic transactions on the shared subscriber state, according to the requests they process. Each request is associated with an independent procedure implemented in each worker. The workers control the RAN and user plane components, via the north-bound APIs, in an SDN-like approach that remains in line with 5G. Towards the UE, a front-end similar to those used in web services facilitates the communication with the core workers.

D. NETWORK MANAGEMENT

An AI-enabled, autonomous management brings together the different telemetry and monitoring streams in the intelligence layer. This layer shall provide operators with a sophisticated management interface, which enables administrators to express their requirements in abstract human-friendly format that will be translated to network management intents. The intents will be processed by an intent engine, resulting in policy, deployment, scaling, placement, and configuration decisions being made based on a goal oriented management system. The system comprises multiple control loops handling the different types of components. The control loops for the core network services are indicated in Figure 10: one for subscriber state, workers, and front-ends each. The subscriber state control loop will be responsible for placement and scaling of the distributed storage system, based on available resources and UE distribution. Similarly, the worker control handles scaling and placement of workers, also taking into account available resources and current load. Additionally, this control loop will be responsible for the management of the procedures, loading, unloading and updating them to workers as their local use cases demand. Of course, the front-ends have to be placed and scaled in the same manner, through a control loop. To ensure request handling efficiency, the load balancing of RAN and front-ends is steered. The RAN control loop will be split into real-time and non-real-time, following the Open RAN approach. The management system can orchestrate these loops intelligently, by distributing Intent Management Functions (IMFs) [45] as AI agents for local intent enforcement throughout the topology.

For efficient management a deep and comprehensive understanding of the current, as well as the historical state is paramount. A knowledge plane, realized in the

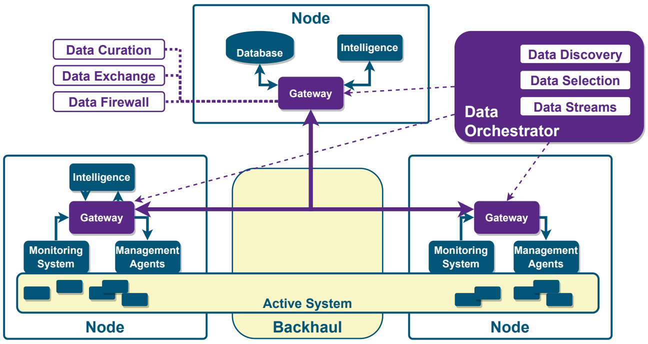


FIGURE 11: ON: Distributed Data Processing

distributed architecture depicted in Figure 11, allows the formation of such understanding. Gateway services are deployed on network nodes, facilitating management, intelligence and monitoring agents spread across the infrastructure. These gateways handle curating, exchange and fire-walling of data. A data orchestrator coordinates discovery and selection of data, while also managing (establishment of) data streams.

E. RESULTING ARCHITECTURE

Combining everything leads us to the layered view presented in Figure 12. The bottom two layers exemplify a network combined of terrestrial and non-terrestrial nodes, including satellites, airplanes, low- and high-altitude platforms as well as maritime vessels and cellular nodes. Some nodes are designated cloud nodes, where virtualized CP functions can be executed. Above the infrastructure, we see the CP fabric which creates a network spanning all CP nodes. Note that for the purpose of visual clarity, we do not include intermediary nodes in the upper layers. Next, we have the three core network services split into different layers. By splitting them, we can visualize more clearly how the workers and front ends do not have horizontal interfaces, while the storage nodes have. On the second-highest layer, we find the network of telemetry probes, which collect monitoring and other information to be processed by the analytics and management system. And finally, at the very top, we have the distributed management agents representing local, regional, and end-to-end control loops, as well as the IMFs and operator interfaces. The key observation is that the different service layers do not all have to be distributed to all nodes or even equally. Front-end nodes can be deployed closer to access nodes, while workers can be located at intermediate or central nodes, to be shared between access nodes, if capacity allows. This provides greater flexibility for placement decisions leading to a more dynamic service orchestration, where momentary needs of applications can be addressed more efficiently.

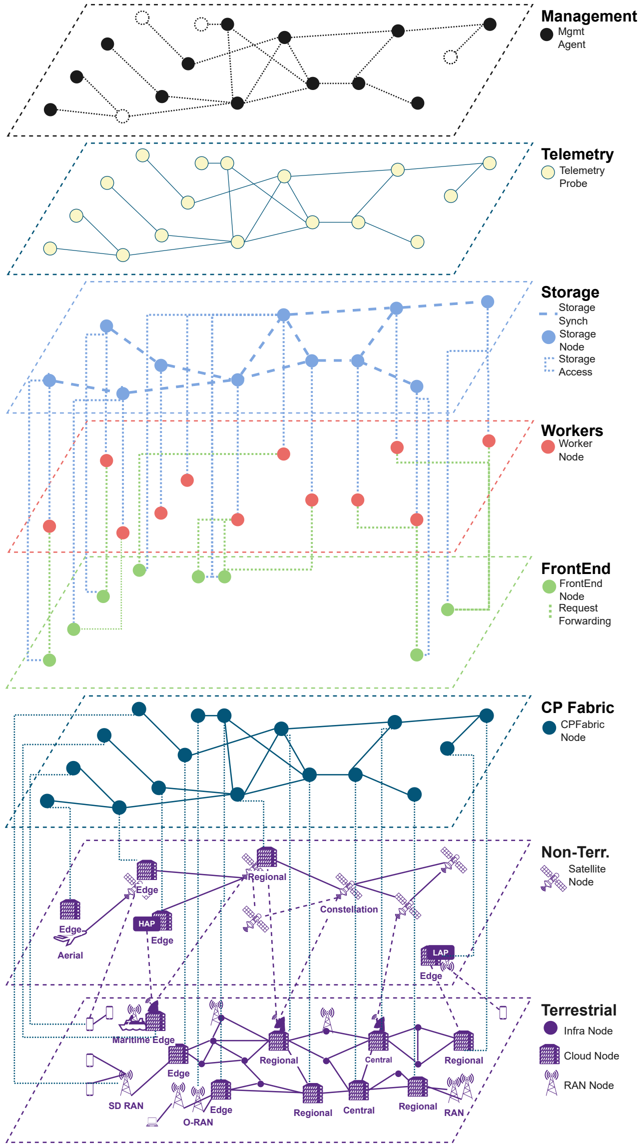


FIGURE 12: Organic 6G Network Layers: Services & Infrastructure

VI. CONCLUSION

In this article, we provided an overview of the ongoing research and identified a lack of requirements, approaches, and innovative architectural proposals. We addressed these short-comings through our presentation of technological requirements and premises for future mobile networks. Based on the initial IMT-2030 and 6G mobile networks research, one can predict a significant increase in system complexity. This complexity will pose insurmountable challenges, if it is not addressed in a holistic way from the overall architecture. As a solution, we presented the Organic Networks concept and high-level architecture. The pillars of organic networks are the restructured core network, the zero-touch control plane fabric, the disaggregated access network, the support for diverse x-hauls, end-to-end telemetry and the intent-based management system. With its ability to morph and adapt, we believe Organic Networks to be the architectural approach needed, to address future application and infrastructure requirements. Organic networks are aligned with the architecture principles postulated in [20], providing in particular

- a system designed for automation (2) through its distributed management agents and comprehensive telemetry,
- flexible & capable of adapting to different network topologies (3),
- scalable from small to large networks (4),
- resilient against disruptions (5),
- implement NF separation of concerns (7) and
- are simpler than 5G thanks to the CN restructuring (8).

We will continue to develop ON within the Open6GHub[2] project and beyond. The architecture needs to be further developed and made more concrete. NF placement algorithms capable of handling the different service requirements with regard to distribution and availability need to be developed. Our goal is to create a prototypical implementation based on the Karlsruher Institute of Technology (KIT)'s Kademlia-directed ID-based Routing Architecture (KIRA) [44], Fraunhofer Institute for Open Communication Systems (FOKUS)'s Open5GCore[3], and Network and Edge Data Management Interface (NEMI)[4] among others. The specific technologies suitable for the prototype need to be identified. For example, the best protocol stack for CP communication or a suitable distributed storage solution, that can handle unreliable links, need to be found.

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