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Towards Programmable Infrastructure for Organic & Flexible 6G Networks

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ABSTRACT The next generation of wireless mobile networks will be driven by software and infrastructure virtualization. At the same time, the underlying hardware will become more diverse. Edge, intermediate, and central network nodes will allow distributed deployments of scale never seen before. Non-terrestrial networks, nomadic networks, and networks in networks promise more dynamicity, changing their topologies over time in predictable and unpredictable ways. To handle complexity and dynamicity, a highly flexible and adaptable network is required. The key enablers of this complex digital communication system will be programmable infrastructures. From programmable access and flexible backhauls to zero-touch, adaptable, and resilient control planes, we conducted research into advanced programmability at different layers of the network, within the Open6GHub project. In this article, we present innovative solutions for advanced programmable network infrastructure and show why they are essential for our vision of the programmable infrastructure of future wireless mobile networks.

INDEX TERMS 6G, Mobile Wireless Networks, Organic 6G Networks, Programmable Infrastructure, Programmability, Reconfigurability, Software-Defined Networks, Software-Defined Radio

I. INTRODUCTION

PROGRAMMABLE infrastructures are becoming the foundation of communication networks through technologies like Software Defined Networking (SDN) and Network Function Virtualization (NFV) [1]–[3]. This is the case for fifth and future generations of wireless mobile networks [1]. For example, the 5G System (5GS) [4] uses a programmable User Plane Function (UPF), separated from the control plane via a dedicated interface. Many Mobile Network Operators (MNOs) deploy their core networks as Virtual Network Functions (VNFs) in data centers, using virtualized infrastructure. Furthermore, many public and private network operators take advantage of SDN technologies to create networks that can react more flexibly to the various demands for traffic and services and allow for more efficient use of network resources [5]–[7]. But 6G networks will require more advanced programmability, allowing more than these limited adjustments [3], [8]. They must be able to change dynamically, efficiently control traffic, and be able to self-heal [9]. As networks become more complex, programmability of all components of the end-to-end system should be considered and feasible approaches need to be investigated. From Radio Access Network (RAN) to front- and backhaul, and from edge to core, mobile wireless networks form a complex system whose individual components require programmability approaches customized to their specific characteristics.

In this article, we present several innovative programmability solutions to improve the adaptability of 6G networks. Our project Open6GHub was the context for research and demonstration of these solutions. Programmable RAN allows virtualization of radio resources for efficient utilization. Flexible, dependable backhauls provide the low latency, high throughput connectivity between edge and central network nodes. Zero-touch control plane connectivity is essential to create a reliable but dynamic control plane, where nodes can join and leave the network aligned with network dynamics without affecting operation. Ideally, Non-Terrestrial Network (NTN) components should also be integrated into this control plane connectivity, so that 6G resources can be controlled by a coherent 6G control plane. A unified, stream-lined, control plane continuum architecture for both core and radio access networks improves signaling paths and helps coordinate decision points. NFV migration and placement optimization improve the utilization of edge, network, and central resources. Adaptive networking and reconfigurability concepts such as nomadic networks allow the network infrastructure to be changed through mobile nodes and adjustable links.

When all of these technologies are combined, on top of already established programmability solutions, full end-to-end network programmability can be achieved. This enables a higher degree of autonomy, flexibility, and efficiency in mobile network operation, facilitating the use of artificial intelligence and machine learning to create advanced autonomous networks.

The remainder of this article is structured as follows. Section II discusses the concept and state-of-the-art of programmable networks as relevant to the presented work. Section III gives an overview of advanced RAN programmability. Next, Section IV discusses front- and backhaul programmability. The control plane fabric is introduced in Section V followed by the discussion of control plane services in Section VI. VNF migration and placement solutions are presented in Section VII. In Section VIII, we present approaches to adaptive network deployments. Section IX discusses physical and logical reconfigurability. Finally, we explain how these technologies come together to enable the next generation of mobile communication networks in Section X, before concluding the article in Section XI.

II. PROGRAMMABILITY OF NETWORKS

A system is programmable if its behavior can be changed by rewriting the programs it executes or by replacing them against different ones. The term *network programmability* is used to denote the capability to change the behavior of a communication or computer network [10], [11]. This is achieved, through altering the behavior of network devices by replacing, updating, or influencing their functionality during run-time through an interface such as an Application Programming Interface (API). These interfaces can be accessible locally or remotely depending on the device.

The behavior of a network can be changed in various ways. One can alter the behavior of the network itself, i.e., the way it transports data: Changing the way data flows from source to destination, e.g., by altering routing tables or forwarding rules as in SDN [12], [13]. SDN tries to increase the flexibility of network behavior by decoupling parts of the router's control plane from its hardware. Routing decisions are outsourced to an SDN controller that can be programmed by the operator, whereas the routing protocols and routing logic implemented by the vendor on the router could not be changed easily, i.e., its functionality could be considered to be fixed. The widely used OpenFlow protocol standard [14] provides an API to configure the forwarding rules inside switches or routers. The programs (SDN apps) running on an SDN controller can then flexibly change the routing behavior, even down to the fine-granular level of individual flows, and also allow for fast development cycles. This is shown in Figure 1 in an abstract network whose nodes are programmed by a controller entity. The controller usually communicates with its controlled nodes via a dedicated control plane network that is separated from regular data plane traffic. Moreover, real-world deployments use multiple distributed controller entities for scalability and redundancy reasons, but this comes at the cost of high complexity, complicated interdependencies, and intricate failure scenarios [7].

Another approach for network programmability is *Segment Routing over IPv6 (SRv6)* [15], where flexible routing policies can be combined with a flexible invocation of certain functions in intermediate systems. A Segment Routing Header contains a list of Segment IDs that can encode path segments or function invocations at certain segment routing endpoint locations. These functions are, for example, encapsulation or decapsulation functions combined with certain lookup behaviors. A practical application is suggested in [16] where SRv6 can be used to realize the user plane of mobile networks (UPF) and its statelessness is used to provide a more efficient replacement for GTP-U. Compared to SDN this approach allows for more distributed realizations, since Segment IDs can be distributed using ordinary routing protocols.

However, approaches such as SDN and SRv6 Network Programming are limited to the use of existing forwarding functionality inside the SDN or SRv6 routers, i.e., it cannot arbitrarily change packet processing within the data plane. For example, only certain IPv4 and IPv6 header fields can be used for match filters, and there are limitations of the available functionality with respect to packet handling such as Quality of Service (QoS) support.

To allow directly altering the processing of packets, there exist approaches such as Programming Protocol-independent Packet Processors (P4) [17] and Extended Berkeley Packet Filters (eBPF) [18]. P4 is an open source programming lan-

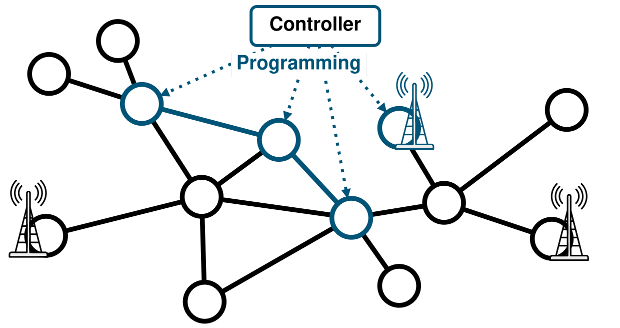

FIGURE 1: SDN: The data plane traffic of a network is altered by a centralized controller programming forwarding decisions.

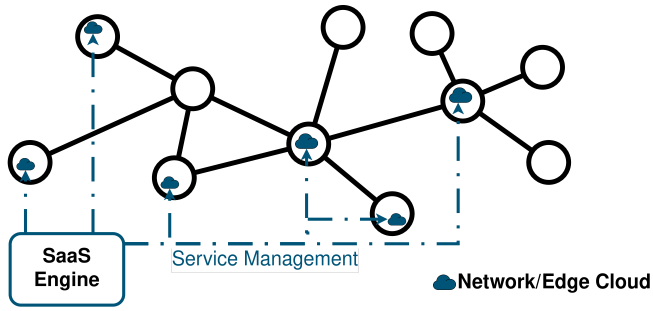

FIGURE 2: Edge & Network Clouds: Throughout the network there are nodes with computation and storage capabilities, available to connected devices. The life cycle of the services is managed by a Software as a Service (SaaS) engine.

guage developed under the Linux Foundation and mainly targeted at intermediate systems such as routers and switches [19] whereas eBPF supports programmability mainly in the end-systems. Nevertheless, P4 is also used in programming hardware solutions, so-called infrastructure or data processing units, that are often used in end-systems in (edge) cloud computing contexts. The advantage of P4 and eBPF over early approaches such as the Click Modular Router [20] is their conceptual platform independence.

This principle of modularizing and isolating software functions has also shaped modern carrier networks and forms the basis of NFV. In NFV, traditional network middleboxes are replaced by VNFs – software implementations of network functions that run on virtual machines or containers (then called Cloud-native Network Function (CNF) [18]) hosted on commodity hardware. These VNFs can be combined and orchestrated into end-to-end Network Services (NSs), allowing operators to create complex service chains with flexible deployment, scaling, and management, while reducing the dependency on specialized network appliances [21]. The flexibility of NFV also enables the execution of non–network-specific application workloads, extending the use case beyond traditional Network Functions (NFs). Building on this capability, the same virtualized infrastructure can also support application-level services, a broader concept commonly referred to as edge computing or in-network cloud [22]. Since end devices often have limited computational, storage, and energy resources, some services or service functions cannot be executed locally and must run elsewhere in the network. With NFV and edge computing, these workloads can be flexibly placed on network nodes, edge clouds, or data centers, taking into account both available resources and latency requirements. This approach allows services to be executed closer to users when necessary, improving responsiveness and user experience while leveraging the full potential of the virtualized infrastructure. This concept of edge computing is visualized in Figure 2, where some of the network nodes have cloud capabilities indicated by a cloud symbol. While the in-network cloud concept allows the provision of Over-the-Top (OTT) services to users, the available resources can also be leveraged by the network itself, e.g., through the dynamic placement of VNFs based on load patterns.

Thanks to the adoption of NFV in both the control and data plane, the behavior of the network can also be adapted by dynamically modifying, scaling, or redeploying VNFs. Such flexibility is facilitated by Management and Orchestration (MANO) frameworks, including Open Source MANO (OSM) [23] or Open Network Automation Platform (ONAP) [24]. These frameworks can orchestrate NSs that combine traditional hardware-based network functions, VNFs, and CNFs, allowing operators to balance performance and flexibility according to service requirements.

Figure 3 shows an example of a MANO system managing NFs across multiple nodes of a network. An NFV orchestrator uses a set of VNF managers to deploy network services composed of multiple VNFs. The Virtual Infrastructure Manager (VIM) takes care of provisioning the virtual resources from the infrastructure. Operations and Business Support Systems (OSS/BSS) (not shown) steer the MANO system.

Several Standards Development Organizations (SDOs) and open source projects work together to enable the creation of so-called Telco Clouds [25], [26]. The "European Telecommunications Standards Institute (ETSI) Industry Specification Group NFV has been the primary standardization body responsible for the development of [NFV] [...]" [26]. Their work on MANO is the reference for OSM. The 3rd Generation Partnership Project (3GPP) introduced the Service Based Architecture (SBA) with the 5GS to create a NFV friendly system, but the architecture is still influenced by the previous generations and cannot fully take advantage of this paradigm [27]. SDN and NFV MANO rely on a control plane network that must be configured correctly for each component to be controllable. But in our view, the complexity and dynamicity of 6G networks will make the establishment and maintenance of the control plane network exceedingly difficult and flexible, autonomous solutions are needed.

With Cloud RAN, similar ideas are applied to the RAN. The first goal was to improve resource usage and energy efficiency through the separation of Remote Radio Head (RRH) and Based Band Unit (BBU), to cloudify the BBUs

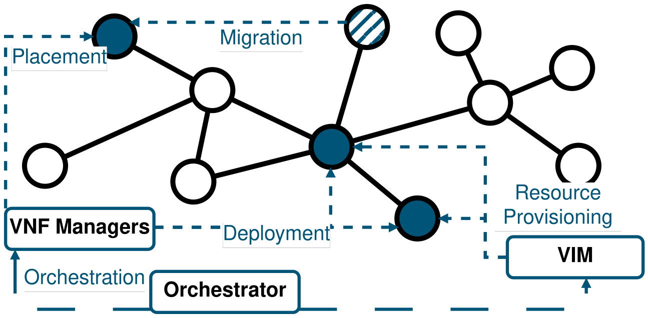

FIGURE 3: NFV MANO: an NFV orchestrator deploys a network service through VNF managers using resources provided by a VIM. It makes placement decisions depending on available resources and the requirements of the service. When an existing NF's placement needs to be changed, it can be migrated or re-deployed to another node.

and serve multiple RRHs from a single location [28], [29]. In the context of 5G, the RAN is further split into Radio Unit (RU), Distributed Unit (DU) and Central Unit (CU), providing additional options for functional deployment in so-called splits and potential for virtualization. However, virtualization of the RAN is non-trivial, given the fact that components like the DU implement signal processing tasks that are computationally intensive and have tight real-time constraints.

In addition, further programmability of cellular access networks comes with the introduction of Open RAN [30], which specifies a disaggregated architecture with open interfaces between RU, DU and CU, promoting vendor independence and flexibility. It introduces the real- and non-real-time RAN Intelligent Controllers (RICs) allowing the deployment of xApps and rApps in real- and non-real-time control loops of the RAN. Together, virtualization of the RAN and the introduction of xApps and rApps, ask for flexible software solutions that can adapt dynamically to different load situations and utilize heterogeneous systems for signal processing and network management. However, these additional control loops could potentially conflict with core network decisions, and the RAN-Core coordination has to be strengthened to prevent service degradation.

In addition, the behavior of the infrastructure as such is changed through programmed adaptation, e.g., changing lightpaths in optical networks [31], or sending Unmanned Aerial Vehicles (UAVs) carrying radio equipment to specific locations to meet coverage and service demand under automatic, programmed control – not just manually [32]. We subsume this under the term *reconfiguration*. Figure 4 illustrates how a network topology is altered through reconfiguration: nodes and connections are added and removed.

Bringing these technologies together, as illustrated in Figure 5, we can appreciate the capabilities of existing network programmability solutions. Through these, many new use cases have been enabled and many issues of static networks have been addressed. But there is still work to be done. In the following sections, we discuss several solutions under investigation to push network programmability further towards the capabilities required for future 6G networks and beyond.

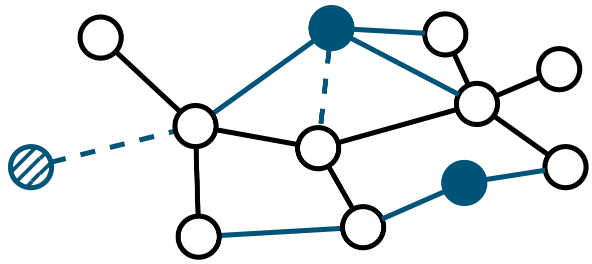

FIGURE 4: Network Reconfiguration: The network topology is altered programmatically. Nodes and links in blue are added or altered. Hatched nodes and dashed links are removed.

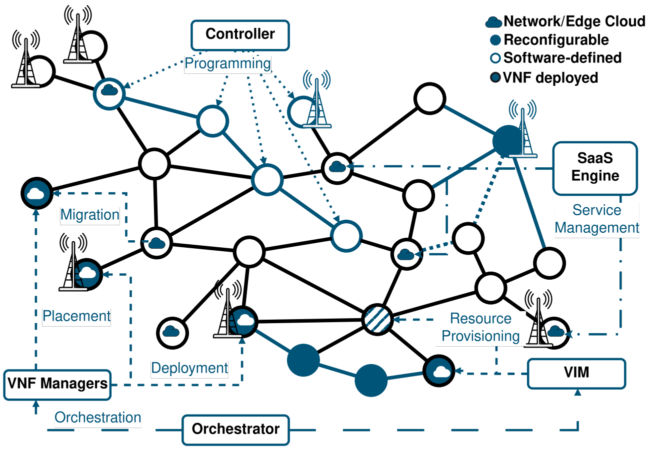

FIGURE 5: Programmable Networks: SDN, Edge & Network Clouds, Reconfigurability and MANO

III. PROGRAMMABLE RADIO ACCESS NETWORKS

RANs are evolving at a fast pace. Toward 6G, they promise to offer greater flexibility, programmability, higher bandwidth, and operation on new frequency bands. However, testbeds for these systems do not match this progress, limiting real-world experimentation and performance evaluation of emerging technologies. While powerful hardware platforms are available, software implementations lag behind. Existing testbeds and frameworks often do not simultaneously provide end-to-end system integration, high throughput, and real-time operation. To address this gap, we focus on programming frameworks and experimentation platforms that enable the development of high-performance wireless communication systems using the available compute platforms (i.e., CPUs, GPUs, and FPGAs).

A. FUTURESDR

FutureSDR[1] is a novel Software-Defined Radio (SDR) framework designed for heterogeneous architectures. This heterogeneity spans three dimensions: platforms (e.g., Android,

[1] https://github.com/futuresdr/futuresdr

Windows, Linux, and the web), processor architectures (e.g., x86, ARM, and WebAssembly), and compute types (e.g., CPU, FPGA, and GPU). FutureSDR is implemented in Rust, a modern, memory-safe, strongly typed systems programming language that provides first-class support for asynchronous programming. Despite its novel design, the main abstractions of FutureSDR are familiar to practitioners in the domain. It uses *blocks*, which encapsulate individual steps in a signal-processing chain, such as filters, arithmetic operations, or synchronizers. These blocks expose input and output ports that can be connected to form a *flowgraph*. Individual signal processing steps are executed as *tasks* that are scheduled by the user-space application, enabling FutureSDR to implement custom scheduling strategies tailored to the specific application. Such schedulers can exploit knowledge of the application's data flow to optimize for different performance objectives (e.g., balancing throughput and latency), which is not possible with existing frameworks like GNU Radio.

While FutureSDR is primarily a CPU-based framework, it is the first to enable efficient integration of hardware accelerators such as GPUs and FPGAs. This is achieved through support for custom buffer implementations that interface directly with accelerator memory, like staging buffers for GPU integration or DMA buffers for FPGAs. FutureSDR blocks are not bound to a specific buffer implementation but can be instantiated with any buffer type that implements a common interface. This abstraction introduces no runtime overhead, as the compiler generates specialized code for each buffer type, eliminating the need for indirection through dynamic dispatch.

B. IPEC

Inter-Processing Element Communication[2] (IPEC) is a framework for generating streaming-based FPGA accelerators with complex interconnect structures [33]. A DSL embedded in Python enables the user to describe a data-flow graph of the overall computation. IPEC uses this information to generate a larger accelerator, which can comprise many specialized accelerators as well as heterogeneous protocols, memories, and interconnects.

IPEC interfaces with the open-source TaPaSCo [34] FPGA shell, which allows the generated systems to directly access available peripherals, such as HBM, 100G ethernet ports, or specialized RF hardware available on some devices.

In combination with FutureSDR, IPEC can provide acceleration by moving not only individual blocks of the signal-processing chain to the FPGA, but larger parts of the flowgraph including data-flow edges. This was demonstrated by implementing a physical-layer subsystem with the ability of moving parts of the flowgraph at runtime between FPGA and CPU using both frameworks [35].

C. HELIX

While IPEC automates the process of creating hardware designs from processing elements, it does not itself provide the advanced signal-processing implementations required for state-of-the-art wireless communication systems. This gap is addressed by HELIX,[3] an FPGA-based experimentation platform with real-time capabilities [36]. It is built on AMD/Xilinx RFSoC-based systems, which are widely used in both research prototyping and practical wireless deployments. HELIX provides an integrated environment for high-bandwidth PHY processing, runtime control, and interoperability with external software stacks, and it can be used either as a standalone platform or as a component within O-RAN-style systems. Its design supports experimentation across different deployment modes and frequency ranges, including sub-6 GHz, 28 GHz, and 60 GHz, while retaining the flexibility to interface with additional frontends as they become available. Results show data rates of up to 1.2 Gbps with 418 MHz of bandwidth and 256-QAM modulation, as well as bidirectional end-to-end latencies down to 500 µs. The versatility of the platform is demonstrated through its integration in research prototypes, including an Integrated Sensing And Communication (ISAC) testbed.

FutureSDR, IPEC, and HELIX are released as open-source software, supporting accessibility, reproducibility, and community-driven development.

D. SCALABLE HARDWARE TRANSMISSION BUFFER DESIGN

6G promises ultra-high data rates with low latency while maintaining a high level of connectivity. While a software-based control plane is unavoidable for flexibility and programmability, a hardware accelerated data plane helps to meet 6G's strict requirements while keeping the energy budget in check. Especially crucial for the scalability of the data plane is the architecture of the transmission buffer in the Data Link Layer (DLL). The DLL handles important tasks such as resource scheduling and reliable transmission via Hybrid Automatic Repeat Request (HARQ) and is part of the DU.

While it is straightforward to scale a software-based transmission buffer solution with the number of active devices in the network, a hardware-based solution offers clear advantages in throughput, latency and energy, albeit at a higher implementation complexity. To address this we developed two sharded transmission (TX) buffer designs based on singly linked lists (Fig. 7), which enable flexible memory allocation for virtually arbitrary numbers of devices while keeping the control overhead low [37]. Both designs support parallel read/write operations, that is without any type of memory access arbitration, and a dedicated delete operation, ensuring efficient (H)ARQ handling. The first design stores control information in dual-port SRAM (SRAM-based), the second relies on register arrays (RA-based).

[2]https://git.esa.informatik.tu-darmstadt.de/ipec/ipec

[3]https://github.com/IMDEANetworksWNG/HELIX

Synthesis results on a AMD Zynq UltraScale+ MPSoC ZCU102 show that the SRAM-based design scales efficiently to more than 100,000 queues, with detailed throughput and latency evaluations performed for up to 512 queues. The SRAM-based variant exhibits excellent scalability, while the RA-based design achieves the lowest latency and highest throughput at smaller scales. We observe mean packet sojourn times as low as 15.6 ns (RA-based) and 33.2 ns under moderate load, both well below the 100 µs target for 6G. Even under full load with 512 queues served in a round robin fashion, average latencies remain within 42.7 µs (RA) and 17.5 µs (SRAM), while sustaining throughputs above 100 Gbps.

As the transmission buffer itself is a plain hardware component, it is only useful within the increasingly software defined RAN if it does not hinder the ability of the control plane to steer Medium Access Control (MAC) layer behavior. Although we do not evaluate such an integration in this work, a hardware TX buffer can in principle be incorporated into a programmable 6G stack, i. e. by exposing a set of configuration parameters like QoS flow activation, per flow queue limits, channel and device priority, the schedule for the upcoming slots etc. to be set by the software-based control plane (see Fig. 6). These results suggest that DLL-level

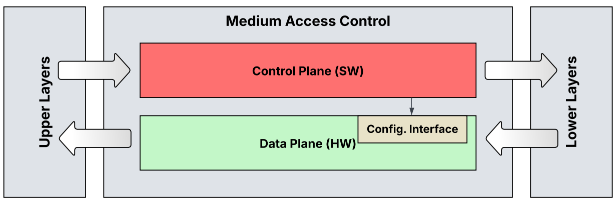

FIGURE 6: A high level MAC architecture that shows a hardware accelerated data plane with a programming interface exposed to the control plane.

hardware acceleration might provide a valuable complement to software-based programmability and performance goals envisioned for 6G.

E. INTRA-RAN DATA FORWARDING AT THE MAC LAYER

While hardware acceleration effectively reduces processing delays, architectural inefficiencies in the standard protocol stack also impose avoidable latency penalties. In standard network topology, the architecture enforces a rigid routing path where the traffic between User Equipment (UE) attached to the same gNodeB (gNB) is typically routed up through the Core Network before being forwarded to the destination. This introduces unnecessary propagation and processing delays.

To mitigate this, we developed a shortcut mechanism located directly within the MAC layer of the gNB [38]. By maintaining a local mapping of UE identifiers, the MAC layer can intercept eligible intra-RAN data packets and forward them directly to the destination UE's downlink queue. This effectively bypasses the upper layers of the gNB and the Core Network entirely for eligible local traffic.

We implemented this logic as a proof-of-concept within the srsRAN project, modifying the higher-layer DU processing.

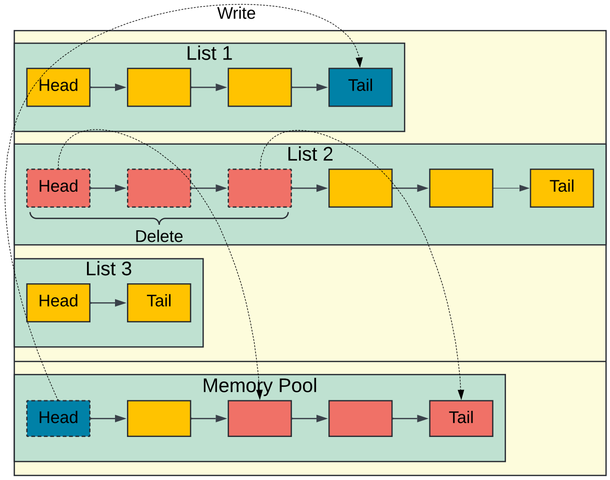

FIGURE 7: Logical structure of the TX buffer architecture, depicting an array of lists with one list serving as memory pool. [37].

Experimental results in our controlled testbed demonstrate that this not only reduces median round-trip time, but also stabilizes latency variance. By eliminating the variable processing times associated with the Core Network and backhaul transport, the shortcut mechanism provides a consistent low-latency performance required for critical local applications.

F. AI-DRIVEN PROTOCOL SYNTHESIS FOR PROGRAMMABLE 6G ACCESS NETWORKS

Future 6G networks will demand highly adaptive RAN protocols capable of responding to varying spectrum availability, heterogeneous traffic profiles, and dynamic multi-access environments. Traditional protocol designs, based on static rules and manual optimization, are insufficient for these emerging requirements. To address this challenge, we introduce a distributed, AI-driven protocol synthesis framework that autonomously designs and optimizes protocol behavior. As an example, we demonstrate its application to the MAC protocol in programmable wireless infrastructures for two major broadband technologies deployed in unlicensed bands: 5G New Radio Unlicensed and Wi-Fi [39], [40].

Our approach leverages Multi-Agent Deep Reinforcement Learning (MADRL) to enable network nodes to collaboratively learn and refine MAC behavior in a decentralized or centralized manner. Instead of adjusting individual parameters in isolation, the framework synthesizes MAC protocols from atomic functional building blocks, such as rate control policies, retransmission functions, etc. These blocks are composed dynamically, enabling the creation of new protocol behaviors tailored to real-time network conditions, including dense unlicensed coexistence (which is important for 5G NR-U) and mixed traffic with stringent latency or reliability requirements.

Unlike traditional learning systems that rely solely on centralized intelligence and may face scalability and latency bottlenecks, our design supports both centralized and fully distributed learning and execution, where each node autonomously adapts based on local observations and limited neighborhood information exchange. This aligns with the 6G vision of edge-native AI, reducing control overhead and improving robustness against topology changes and non-stationary traffic patterns.

To demonstrate the practicality of our solution, we deploy the system in ContainerNet-based emulated network environments [41], where Kademlia-directed ID-based Routing Architecture (KIRA) [42] provides autonomic connectivity and node discovery (see Section V for details). This setup enables closed-loop learning and inference in realistic multi-node scenarios, and supports distributed execution where computational and learning resources are spread across the network. It also allows end-to-end validation of our synthesized protocols on real wireless hardware under realistic latency, mobility, and network dynamics.

IV. FLEXIBLE & DEPENDABLE XHAUL

The transition to 6G networks demands innovative solutions that ensure reliable connectivity across diverse infrastructure configurations while maintaining cost-effectiveness. Our framework establishes robust connections between 6G base stations and core network infrastructure, ensuring high availability in Backhaul networks. This implementation focuses on developing a multipath Virtual Private Network (VPN) system that optimizes traffic distribution across heterogeneous network paths, specifically integrating Ethernet and satellite communications.

The proposed multipath VPN architecture integrates three primary components that work in concert to ensure optimal traffic distribution and network reliability: path management, traffic schedule engine, and network interface abstraction as shown in Fig. 8.

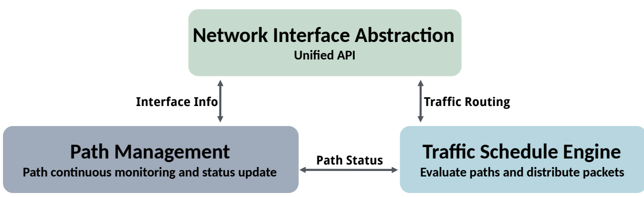

FIGURE 8: Architecture of multipath VPN for traffic backhauling

Network Interface Abstraction provides a unified interface handling mechanism that enables transparent communication across different network types while maintaining optimal performance characteristics. This abstraction layer manages the complexity of multiple network interfaces while presenting a consistent interface to upper-layer services, enabling efficient traffic distribution and optimal resource utilization.

At the heart of the system lies the Path Management System, which serves as the primary observational component. This subsystem continuously collects real-time performance metrics across all active paths, enabling comprehensive network visibility. Through sophisticated monitoring mechanisms explained in our article [43], it tracks latency, throughput capacity, packet loss and jitter to identify potential bottlenecks before they impact system performance.

The Traffic Schedule Engine implements sophisticated routing logic to optimize data flow across multiple paths while maintaining packet sequence integrity. This subsystem employs a multi-faceted approach to path selection, combining several complementary strategies to achieve optimal performance. The algorithm's foundation is built upon a weighted round-robin scheduling mechanism, which provides a baseline for balanced traffic distribution across available paths. This foundation is enhanced through the implementation of a multi-arm bandit algorithm that dynamically adjusts path weights based on real-time performance metrics. The bandit algorithm continuously learns from path performance data, allowing the system to adapt its traffic distribution patterns in response to changing network conditions. Preliminary performance results were published in [43].

To further optimize path selection, the system incorporates machine learning-based algorithms that analyze historical traffic patterns and network conditions. These Machine Learning (ML) components enable predictive routing decisions, anticipating potential network congestion and packet delivery issues before they occur. The ML framework processes comprehensive network metrics, including latency patterns, throughput variations, and packet loss statistics, to identify optimal routing strategies. A path-stickiness mechanism was implemented to address out-of-order packet delivery challenges [44]. This component maintains packet sequence integrity by preferentially routing related packets through the same path when possible, while still allowing for dynamic path switching when network conditions warrant it. The stickiness algorithm balances the need for consistent packet ordering with the requirement for optimal network utilization, implementing a sophisticated decision-making process that weighs these competing demands.

The integration of these multiple approaches creates a robust and adaptive traffic distribution system. The algorithm continuously monitors network conditions and adjusts its routing decisions accordingly, ensuring optimal performance while maintaining packet sequence integrity. Through this multi-faceted approach, the system achieves both efficient traffic distribution and reliable packet delivery, even in challenging network conditions.

V. CONTROL PLANE FABRIC

Programmable infrastructures require reliable *control plane connectivity* between devices and NFs. A typical example is the connection that an SDN controller requires to program its SDN switches. This connection often uses a separate 'out-of-band' Control Plane Network (CPN) so that the SDN controller can (re-)program its switches independently of the forwarding rules that are currently installed. However, this separate control plane network also requires its own setup, configuration, routing, and management. Out-of-band CPNs must be "highly available, easy to manage and maintain, and cost effective" [5], but come with the burden and complexity of installing and operating two distinct networks as well as adding new failure modalities [7]. Large, complex, and highly dynamic networks (such as 6G networks) make it nearly impractical to use separate out-of-band CPNs. An *in-band* CPN uses the same links for control as for transporting data packets and is cheaper, but comes at the cost of potential circular dependencies on connectivity [6]. Moreover, in 6G infrastructures, one can expect that separate out-of-band CPN connections are impractical and also infeasible, e.g., for wireless backhaul links and links to drones or satellites. In practice, some networks [5], [6] use a hybrid CPN approach, i.e., a mixture of in-band and out-of-band CPNs. Both CPN variants need a connectivity solution that often requires a routing protocol for larger networks (smaller networks may simply use a link-layer solution). The importance of reliable CPN connectivity is also stressed in [7] which lists control plane related outages as cause in 52% of the largest Google's B4 WAN outages.

KIRA is a *scalable zero-touch* routing architecture that provides IPv6 connectivity without manual configuration in all types of topologies. Zero-touch does not only mean without manual configuration, but also includes adaptivity. In this context, KIRA automatically adapts to different underlay topologies and link or node failures in a self-organizing manner. It is ID-based, i.e., network resources keep their address even while changing their connectivity in the topology, e.g., by moving across the topology or becoming multi-homed. It provides self-generated addresses (currently using a 16-bit Unique Local Address prefix and a 112 bit NodeID that is randomly generated), therefore, it does not need any other address assignment mechanism for building its connectivity.

KIRA provides a *Control Plane Fabric* on top an underlying (usually link layer) topology so that control and management entities can exert control over their resources on top of this connectivity, e.g., by creating control connections and sending commands to the resources, gathering monitoring data and so on. Thus, KIRA's established control plane fabric allows one to interconnect all 6G networked resources for all necessary control tasks, e.g., allow for network management and control (SDN, NFV) of the 6G Core network, let 6G core components communicate with each other or with RAN components, and so on. Its properties make it a suitable solution especially for 6G networks, because it also supports non-terrestrial network resources such as satellites or drones as well as nomadic networks. Figure 9 displays the control plane fabric in relation to control plane and infrastructure layers.

In addition to zero-touch IPv6 connectivity, KIRA can provide tightly coupled add-on services that support self-organizing control planes. For example, KeLLy [45] is a scalable and efficient network topology discovery service that provides a complete network graph with low overhead even for topologies with hundreds of thousands of nodes. This can help placement and orchestration services running on controllers in the control plane. Another example is a Distributed

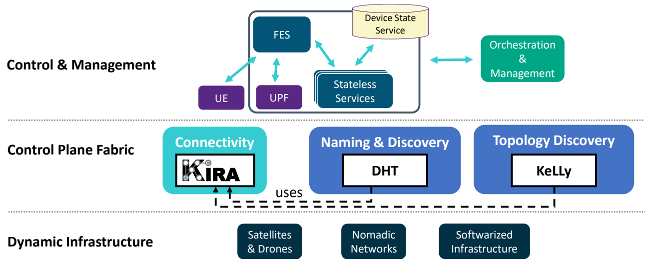

FIGURE 9: Control Plane Fabric: KIRA provides connectivity for the control and management services on top of dynamic infrastructure. [47]

Hash Table (DHT) that can serve as key-value store. Services and resources can register their names themselves so that other entities (e.g., users, controllers, and dependent services) can find them. This functionality supports self-organizing and zero-touch management services [46].

Traditional routing protocols typically require some form of configuration; e.g., administrators need to assign and set router identifiers, IP addresses, or areas to achieve scalability. Therefore, such approaches are not zero-touch as they require some form of configuration, which in turn requires a working CPN leading to a cyclic dependency. Scalable routing approaches for data centers work only in these specific topologies and require a priori knowledge of the topology, which is not suitable for rapidly changing 6G infrastructures (e.g., considering ad-hoc expansion of RAN coverage on-demand using drones). While traditional routing protocols prefer shortest path routes for efficiency, KIRA prioritizes reliable connectivity over route efficiency. KIRA's small routing tables cause path stretch as a trade-off for scalability. However, a KIRA node actually learns shortest paths to all nodes in its routing table. Thus, if certain nodes are contacted frequently, they can be put as additional cached entries into the routing table, thereby allowing to communicate efficiently to them (e.g., especially useful for controllers). KIRA's rediscovery procedure for recovery from failures distinguishes it from other approaches, and it can recover reliably even from drastic failure scenarios where 15% of all links fail randomly and simultaneously in a network with 100 000 nodes [42] or when the network partitions.

Eventually, the Control Plane Fabric provided by KIRA is a foundational enabler for resilient programmable infrastructures as it supplies a connectivity invariant: software updates or configuration changes to networked resources can always be rolled back to a previous working version, because the connectivity to networked resources that run KIRA is provided independently of all other services (except connectivity at the link layer). The benefits and usefulness of this approach have been showcased in several demonstrations for different use cases in future 6G network infrastructures [41], [48]–[50].

VI. ORGANIC 6G CONTROL PLANE SERVICES

Control and User Plane Separation (CUPS) is one of the key tenets of SDN and programmability which was adopted by the 5GS, separating RAN and user plane from the control plane. The 5GS control plane follows a SBA, using Hypertext Transfer Protocol 2 (HTTP/2) protocol to connect NFs while it communicates with the RAN through a separate NG Application Protocol (NGAP) connection handled by the Access and Mobility Management Function (AMF) and by Packet Forwarding Control Protocol (PFCP) with the UPF [4]. This approach improved flexibility and the deployment in virtualized environments. But the 6G control plane services will have to operate in a much more diverse environment with compute capacities available from the central office data centers all the way to the edge and possibly UE [3]. Therefore, it is necessary to further evolve the control plane architecture, to accommodate the network infrastructure of the future.

A. RAN-CORE CONTINUUM

The 5G RAN and core networks are separated through the N2 interface [4]. This made sense historically, as the RAN was focused on the immediate handling of UE connectivity, but with the split into RU, DU and CU as well as technologies like cell-free massive Multiple Input Multiple Output (MIMO), the RAN has become a complex distributed system itself. Furthermore, with Software-Defined Radio (SDR), cloud RAN and Open RAN's RIC the RAN control plane has more powerful capabilities. There problematically emerges a potential for functionality overlap and conflicting decision making by RAN and core NFs. Therefore, RAN and core will need to converge into a continuum, crossing protocol barriers [51]. This will allow improved handling of UE service requests and infrastructure utilization [52]. We propose the organic RAN-Core continuum as shown in Figure 10, as an innovative restructuring of the control plane for 6G networks. The organic control plane continuum is comprised of stateless services implementing procedural control logic of the access and core networks, such as authorization, authentication, session and mobility management, to name a few. It also implements near-real-time RAN control plane services for traffic steering and subscriber management. There should also be environments to support xApps like the Open RAN RICs, to enable deployment specific extension and customization, e.g., though ML agents. Services for positioning and sensing are examples of additional 6G functionality enablers. These services do not communicate horizontally between each other, because their responsibilities are fitted to eliminate the need. This prevents overly complex micro-service chains exchanging requests back and forth to handle UE requests. Instead, they rely on shared database services to store state information about devices, subscriptions, policies and accounting. Thus, the services can be deployed, scaled up and down, and replaced effectively without interfering with each other. So-called Front-End Servicess (FESs) act as proxies between control plane services and the data plane. This way the control plane can be compatible with different generations of user

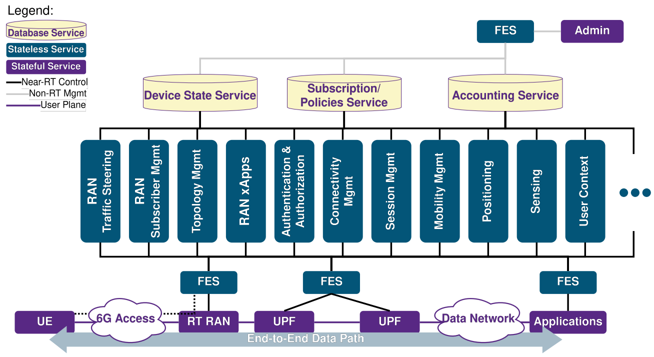

FIGURE 10: Organic 6G RAN-Core Continuum Architecture [47]: various stateless services of the RAN and core control planes communicate with the data plane through FESs and manage system and device state stored in separate data bases.

planes. An administrative interface is available for non-real-time management, such as UE provisioning, policies and intents.

B. THE ORGANIC CORE NETWORK

By taking advantage of the control plane fabric discussed in Section V, the control plane continuum can become more resilient and flexible, in the face of dynamically changing, partially unreliable infrastructure. For the sake of interoperability with existing 5G radio equipment, we prioritize the core services. We implemented the organic core control plane by deploying Open6GCore [53] on top of KIRA [42]. Open6GCore is a 3GPP aligned core network implementation of the organic 6G core architecture. Through its innovative control plane design, inspired by cloud-native web-scale solutions, it aims to be a more flexible improved core network, deviating from the 5G SBA in certain key aspects while striving for compatibility. In combination with KIRA, this creates a reliable, efficient control plane which can handle scale-out, service upgrades and other changes in topology.

VII. NETWORK FUNCTION VIRTUALIZATION

As stated earlier, NFV is already state-of-the-art. But research into aspects like VNF migration and placement optimization can still provide benefits to future mobile networks.

A. VNF MIGRATION

Dynamic migration of VNFs is a key capability for fault-tolerant and programmable 6G infrastructures. In recent experimental evaluations within a containerized environment, open and reproducible migration techniques using open-source components such as Open5GS have been investigated [54]. The testbed was deployed across virtualized edge–cloud infrastructures and explored the migration of both UPFs and Session Management Functions (SMFs).

To enable live migration, we applied Checkpoint/Restore In Userspace (CRIU) to preserve the runtime state of containerized NFs during relocation. While classical CRIU-based restoration successfully maintained container state, it

TABLE 1: Summary of Evaluated VNF Migration Concepts

Aspect	Approach / Scenario	Key Mechanism	Observed Behavior	Trade-offs / Insights
UPF Migration (Stateful)	CRIU-based container migration	Checkpoint/Restore In Userspace	Session interruption after PFCP mismatch	Requires NF state synchronization between SMF and UPF
Parallel UPF Operation	Dual-UPF deployment	Manual session re-attachment	Short disruption (5–10 s), successful reconnection	Effective for controlled switchover; not fully autonomous
SMF Migration (Control Plane)	CRIU checkpoint transfer	NF re-registration via NRF	No session loss, seamless continuity	Migration feasible for control-plane NFs; low impact
SMF-Triggered UPF Switching	PFCP session modification	Dynamic rerouting to alternate UPF	Continuous traffic; zero packet loss	Automation reduces downtime, enhances resiliency
VM-Level Migration Tests	Coordinated live migration	NIC state preservation	Latency spikes < 20 ms, no packet timeouts	Coordination essential for minimal user disruption

did not preserve PFCP sessions, leading to temporary user-plane disruption. To mitigate this limitation, we implemented an SMF-triggered rerouting mechanism, in which the SMF autonomously modifies PFCP session parameters to redirect traffic to an alternative UPF instance without user intervention. The results demonstrated seamless session continuity and negligible latency variation (below 10 second reconnection for manual switchover versus zero packet loss for automated rerouting).

Migration of control-plane NFs such as the SMF proved largely non-disruptive, as the Network Repository Function (NRF) automatically re-registered migrated instances after restoration. Complementary measurements during Virtual Machine (VM) live migration showed that coordinated Network Interface Controller (NIC) state preservation significantly reduces latency spikes (typically < 20 ms). These findings highlight the trade-offs between transparency, orchestration complexity, and session continuity, providing a practical blueprint for resilient NF migration in open, modular 5G/6G testbeds. A high level summary for each approach is listed in Table 1.

B. PLACEMENT OPTIMIZATION

6G's software-only, cloud-native, heterogeneous infrastructure across central, regional, edge, nomadic, and non-terrestrial nodes makes VNF placement a primary lever for response time, resource utilization, scalability, and robustness. "Optimal" is context-dependent and can shift with diurnal demand patterns, so Multi-Criteria Optimization is needed to navigate cost–latency–success trade-offs under capacity and reliability constraints.

To address these competing goals rigorously, [55] employs Mixed-Integer Programming combined with Multi-Criteria Optimization. It streamlines the core into three services—FRONTEND, WORKER, DATABASE—modeled as an ordered chain to keep service placement tractable while preserving realistic request flows. Two complementary MIP formulations are proposed: a request-oriented model for heterogeneous demands and an aggregated model that groups homogeneous requests by ingress and scales independently of request volume. The models jointly minimize installation costs and end-to-end latency while targeting a 100% success rate. They accommodate node capacities, link bandwidth, per-service subscriber limits, and failure scenarios. Trade-offs are explored with the epsilon-constraint method and re-optimization, producing Pareto-optimal operating points rather than a single "best" answer. Numerical experiments on heterogeneous synthetic central–regional–edge ring topologies with hotspots show that tightening latency guarantees shifts installations toward the edge and hotspots, which increases costs. When capacity constraints are active, solutions form service centers and split services across neighboring nodes where needed. The aggregated model scales to very large request volumes, while the request-oriented model provides flexibility for heterogeneous traffic at higher computational cost. Based on the MIP/MCO outputs, the network provider can select an optimal solution depending on the preferences.

A promising extension is to introduce a flexibility metric for placements to favor solutions that remain effective across different scenarios and times of day. These steps pave the way for dynamic re-placement in future core networks that continuously react to the time-varying nature of demand.

VIII. ADAPTIVE NETWORK DEPLOYMENT

A. NOMADIC NETWORKS

Within the scope of organic 6G networks it will be possible to realize new architectural concepts and types of 6G networks [3], [56]. In this domain the so called Nomadic Networks (NNs) represent a significant shift in how network infrastructure is designed and operated. Unlike traditional cellular communication systems like 5G, the concept for NNs for 6G consists of mobile and self-organizing Non-Public Networkss (NPNs) that provide radio infrastructure capabilities while moving [57]. This paradigm shift introduces new architectural challenges and opportunities, particularly in dynamic environments such as large outdoor events, emergency situations, or cross-border activities.

NNs introduce specific Key Performance Indicators (KPIs) that are crucial for evaluating their performance and effectiveness. These include connectivity assumptions, function placement, and mobility support. For NNs, additional KPIs focus on the unique requirements of industrial and tactical applications, which differ significantly from traditional static cellular networks [58]. These newly identified KPIs can be summed up in application clusters that share the same de-

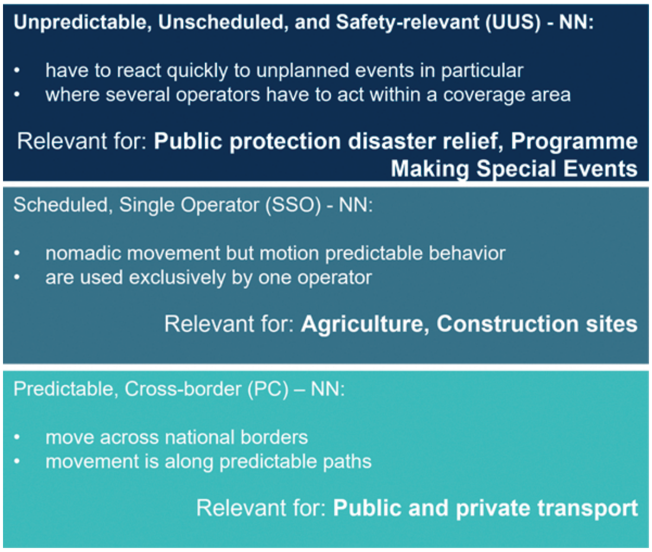

FIGURE 11: NN application clusters: Unpredictable, unscheduled and safety-relevant, Scheduled, single operator and Predictable cross-border NNs.

mands on specific KPIs, as illustrated in Figure 11. These include industry, manufacturing, agriculture, and public services. Each sector has specific requirements that can be met through the deployment of NNs, enhancing connectivity and operational efficiency in mobile environments.

The integration of nomadic networking into 6G will require adaptations in standardization and regulation [59]. This includes addressing functional splits within the RANs, especially on the N2 and N3 interface and the development of a robust backhauling solution via the N6 interface to ensure continuous connection to, e.g., a central cloud server. Additionally, ensuring interoperability with existing systems and maintaining stakeholder trust is critical for the successful deployment of these networks [60].

NNs represent a transformative approach to 6G infrastructure, offering enhanced connectivity and flexibility in dynamic environments. By addressing architectural challenges and defining specific KPIs, NNs can meet the evolving needs of various sectors. Proposed changes to current standards have to be considered to realize this new cellular communication concept for a more adaptable and efficient wireless communication systems.

B. NETWORKS-IN-NETWORK

Besides the NNs approach, organic 6G networking is also an essential part to realize concepts in the field of Networks-in-Network (NiN), representing an approach in the design and operation for sub-networks within the coverage area of an overall communication system, particularly for 5G or future 6G networks [61], [62]. NiN allows for the dynamic adaption and management of available sub-networks or the zero-touch integration of new ones within an overlayer network infrastructure. Different sub-networks can have specific settings to fulfill different QoSs requirements. This approach is supporting diverse applications with varying requirements, especially demands in the scope of ultra-reliable, low latency communication (uRLLC).

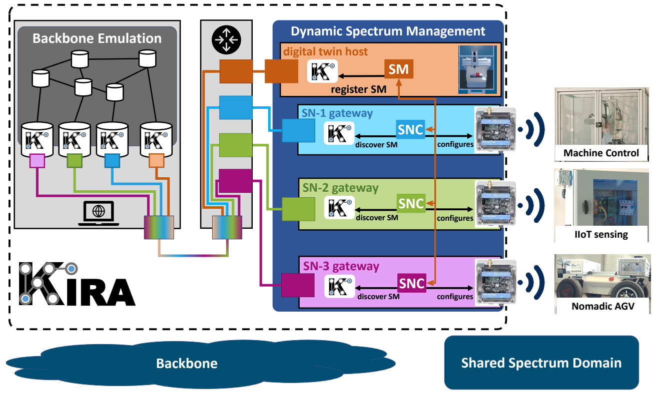

FIGURE 12: Architecture for DSM in an Industrial Internet of Things (IIoT) domain [50]

Our developed Dynamic Spectrum Management (DSM) presents the fundamentals of this approach in combination with the routing protocol KIRA. DSM involves the real-time allocation and management of available spectrum resources of the sub-networks to optimize sub-network performance and meet the different QoS needs of different sub-networks [63]. By leveraging advanced algorithms and machine learning techniques, DSM could furthermore adaptively allocate spectrum based on demand, interference levels, and service priorities. This will ensure that each sub-network receives the necessary bandwidth and configuration to fulfill QoS requirements, thereby enhancing overall spectral efficiency and user experience. Zero-touch realization is an important aspect within the realization of NiN, focusing on automated detection and integration of new or unknown sub-networks. This will lead to reduced human intervention and improved operational efficiency. Via KIRA an automated configuration, monitoring, and optimization of network functions and services can be realized [49].

The NiN approach offers a robust framework for 6G wireless communication systems, addressing the challenges of diverse application requirements and dynamic environments. Enabled by DSM and KIRA, NiN streamline spectrum allocation, enhanced network performance, and reduced operational costs, e.g., for IIoTs scenarios as shown in Figure 12. In addition to this, an integration of the in Section VIII-A described approach of NNs is possible. Combining both concepts will lead to an holistic approach for cellular based wireless communication, especially in the domain of NPNs .

IX. RECONFIGURABILITY

Reconfigurability is the ability of a system to adapt to a changing environment. For example, during a concert, hotspots may require temporary adjustments of the environment, such as scaling the network infrastructure to meet service-level agreements (SLAs).

Reconfiguration can be *physical*, *logical* or a combination of the two. Physical reconfiguration changes the network infrastructure, for example, using drones to deploy aerial small cell base stations, while logical reconfiguration often involves changes at the network and functional level, such as changes in topology or migration and scaling of virtualized functions. Both physical and logical reconfigurations are required to meet the strict SLAs of 6G systems.

Such SLAs often aim for high throughput or ultra-low and guaranteed latencies. Achieving this, however, is a major challenge in practice. One such challenge is the switching time across configurations, causing high variability of latency or loss of throughput, leading to SLA violations. We present two examples to illustrate how to tackle such challenges both physically and logically.

A. LOGICALLY

Logical reconfigurations are particularly useful for applications with strict latency requirements and changing load. One example of such applications are ML services with ultra-low latency requirements. These services are often accelerated by GPUs, for example at a nearby base station, to comply with their strict latency requirements. A single ML service, however, often underutilizes a GPU's processing capacity and furthermore, having one GPU exclusively assigned to each ML service is often infeasible. As a result, multiple services typically share a GPU, thereby improving cost-efficiency.

GPU sharing, however, requires *logical reconfigurability* to dynamically and fine granularly assign resources, such as individual processors of the shared GPU, to services. Moreover, a request to a service with ultra-low latency requirements needs *immediate* access to processors to comply with the SLA, while any unused processors by this service must remain accessible to other services for cost-efficient operation. Hence, a logical reconfiguration mechanism for GPUs used in 6G systems must be fast and provide isolation: fast to adapt to changing loads of services on the fly, while isolation guarantees compliance with latency SLAs.

[64] illustrated such a mechanism specifically for NVIDIA GPUs and proposed to spatially partition the processors of a GPU. The system dynamically assigns these partitions with low overhead at runtime and in between *kernel* launches to different services [4].

B. PHYSICALLY

Physical reconfiguration alters the structure of the network itself to maintain service continuity and meet strict performance requirements. Such reconfiguration is particularly relevant in highly dynamic or spatially distributed environments where the physical medium, whether radio, optical, or aerial, becomes part of the adaptive control loop.

[4]A kernel is a function that executes on the GPU and typically runs between tens to hundreds of µs.

One important class of physical reconfiguration involves adaptive link steering and resource relocation. In aerial and optical access networks, for example, directional links such as free-space optical (FSO) beams must be continuously reoriented to maintain connectivity under changing environmental conditions. The network therefore operates as a physically reconfigurable topology, where each reorientation introduces a short disruption period that must be considered in scheduling and resource allocation. Coordinating such reconfigurations requires a balance between responsiveness and stability. Frequent steering ensures high link quality, yet excessive switching can degrade throughput. Therefore, dynamically allocating serving nodes or beams based on link conditions and expected switching delays can sustain throughput and latency guarantees even in stochastic environments.

The physical network reconfiguration ability with adaptive link steering and resource relocation is very important for the use of integrated sensing and communication (ICAS)-enabled predictive link blockage mitigation techniques. Especially wireless communication links in the millimeter-wave (mmWave) frequency region suffer from blockages of the direct line-of-sight path. Through the ICAS functionality of transceivers, moving objects can be detected and tracked. If a potential blockage is predicted, preventive countermeasures can be executed [65]. This includes the use of an alternative mmWave transmission path through a reflection, but also network reconfiguration through the use of other physical resources (e.g. another base station) or communication links in different frequency bands. Since mmWave links usually provide higher capacity compared to lower frequency bands, the selection of the blockage mitigation measure must include the overall network configuration and current performance and usage parameters.

Another form of physical reconfiguration arises at the optical transport layer, where the logical interconnection of network nodes can be redefined through reconfigurable optical circuits. Here, instead of changing the position of nodes or beams, the physical lightpaths themselves are rearranged to align with current traffic demands and service function placements. By jointly adapting lightpath topologies with the placement and scaling of virtualized network functions, the network can minimize end-to-end delay and reduce queuing congestion without overprovisioning. Such integration of compute and transport reconfiguration, as explored for wavelength-division-multiplexed (WDM) optical networks [66], represents a scalable solution toward delay-optimized backbone infrastructures.

X. TOWARDS FLEXIBLE, ORGANIC 6G NETWORKS

Modern wireless mobile networks are built on top of a partially programmable network infrastructure. SDN, cloud RAN, CUPS, NFV and MANO have already or are being adopted in existing networks. These technologies, however, do not suffice to address the use cases of future wireless mobile networks beyond 5G [9]. Advanced Programmable Access Networks are needed to meet new flexibility, latency

FIGURE 13: High-level Architecture: The user, control and management planes run on the network infrastructure, connected in a control plane network for management and control communication.

and throughput demands. Integrating NTN and other technologies with non-static link characteristics require backhaul adaptation. The control plane needs to not only be more reliable and efficient, but also more resilient so that it can adapt to foreseen changes and unforeseen failure scenarios in a meaningful manner. When the network is segmented, the individual segments should be able to operate on their own. Ideally, full connectivity loss between most larger segments should not be possible, but a truly resilient network design needs to take this possibility into account. Nomadic and reconfigurable networks in networks with diverse front- and back-hauls need to be integrated and exploited appropriately.

We propose an end-to-end system, whose high-level architecture is illustrated in Figure 13. The system consists of management, control, user data, and infrastructure planes. A control plane network is established on top of the infrastructure, to connect the management, control and user data planes. This is essential because the three planes are interwoven, geographically distributed systems whose operation relies on a heterogeneous and dynamic system of networked components (the infrastructure). Services in the management plane provide life-cycle management and configuration of the other planes, operating at non-real-time level and slower. Control plane services handle core network procedures, steering the data flows and control the user data plane components. In the user data plane, access, front-, mid- and back-haul network components implement the actual data transmission.

Where in this architecture do the different technologies we presented belong? To understand this and the relations between the components in more detail, consider the end-to-end architecture in Figure 14. It shows which components are present in which plane and indicates the programming interfaces.

In the management plane, NFV MANO services work together with RAN-Core administration service and Service Management and Orchestration (SMO)/non-real-time RIC. The Operations Support System (OSS) and Business Support System (BSS) use the NFV Orchestrator (NFVO) to manage the lifecycle of NSs. The NFVO orchestrates the NSs through VIMs and VNF Managers. The RAN-Core Administration service is added to the management plane, providing operators the ability to manage RAN-Core specific parameters. SMO and non-real-time RIC from open RAN are also part of the management plane. This RIC can host rApps for advanced analytics and management steering. The VIM provisions virtual network, compute and storage resources for the virtualized control and user plane components, relying on virtualization technologies, such as Infrastructure as a Service (IaaS) and SDN frameworks.

The converged RAN-Core control plane will replace the 5G control plane and the Open RAN near-real-time RIC. Spectrum usage of co-located networks will be coordinated by the DSM. The DSM could be managed by the SMO/RIC and its rApps. SDN controllers are needed to steer traffic flows in the user plane. As the network services will require virtual compute and storage resources, we include an IaaS control plane to represent the services handling these.

In the user data plane, the 6G UPF connects the access to the data networks. It is controlled by the session and mobility services in the 6G control plane. When it comes to the RAN the programmable access technologies FutureSDR, IPEC, HELIX, scalable transmission buffers as well as the AI-based protocol synthesis offer the flexibility needed to support the challenges envisioned, without sacrificing performance. With the ability to incorporate accelerators and optimize MAC for latency or throughput, more use-case tailored RAN slicing is possible. To enable dependable and flexible back- and front-haul connectivity, multipath support with link-KPI awareness taking advantage of the characteristics of alternatives are needed.

In the infrastructure plane, we find a diverse set of technologies, whose characteristics differ from traditional networks. The networks will still use the existing infrastructure as 5G, or upgraded versions with better throughput and latency, but in addition, nomadic and reconfigurable networks will be integrated. Combining terrestrial and non-terrestrial networks, introduces new levels of dynamicity into the system [67]. With Low Earth Orbit (LEO) satellites, for example, introducing periodically changing links that affect traffic paths, and UAVs providing mobile and nomadic network nodes that can offer temporary connectivity. The interactions with nomadic networks need to be understood, so they can be operated in conjunction with the existing networks. The same is true for Networks in Networks. Here, the coexistence and interactions of different networks can cause disruptions that warrant the investigation of mechanisms such as the DSM that serves to coordinate spectrum usage. Furthermore, through reconfiguration the network topology itself can be adapted. When usage patterns change or parts of the network are disrupted, the network needs to maintain QoS or at least basic services as much as possible.

The network connecting management, control and user plane will be provided by a control plane fabric. To ensure dependable operation, the control plane fabric needs to be capable of efficiently connecting the different components. While Figure 14 organizes services and components logically, the actual topology and geographic distribution will be a lot more interwoven. User plane components, of course, are physically restricted to their hardware. Control plane services however, can be deployed across the network in different

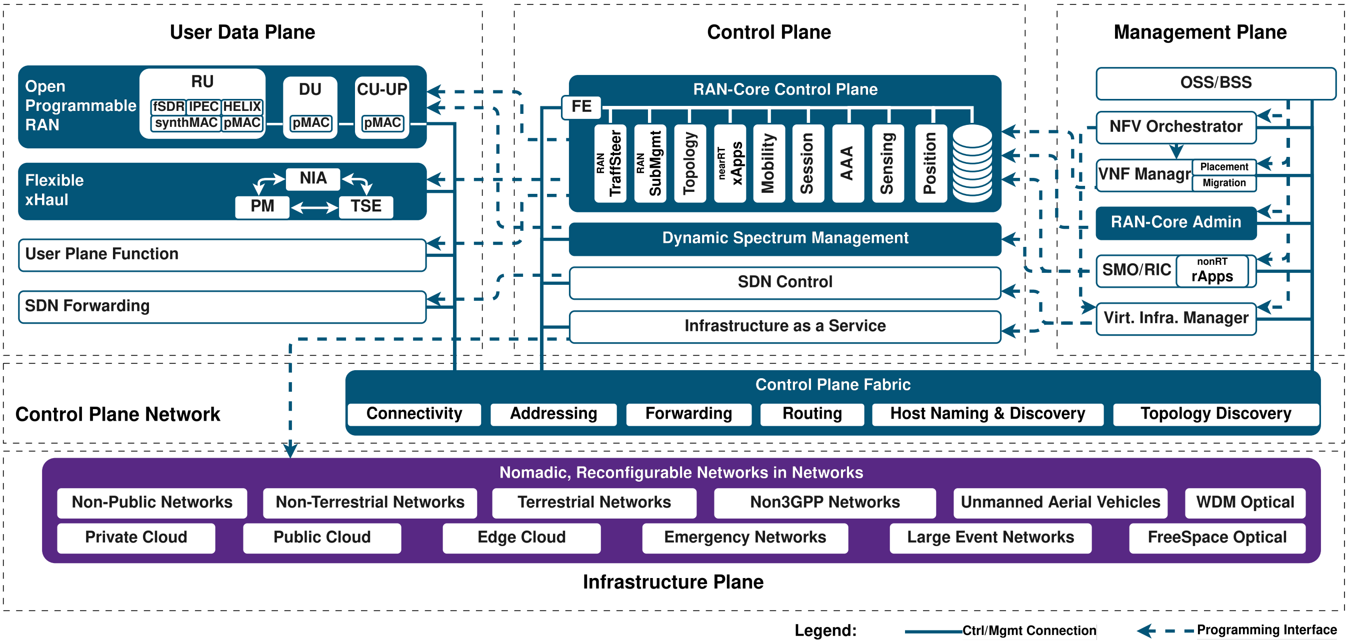

FIGURE 14: End-2-End 6G Programmable Network Architecture: Programmable RANs, flexible xHauls and a control plane continuum communicating via the robust control plane fabric are needed to operate in increasingly diverse, nomadic and reconfigurable networks in networks infrastructure.

locations at different times, depending on the resources and user demand. In fact, near-real-time xApps will require close proximity to the respective access networks, to meet latency requirements. Traffic steering and topology management of access networks may also be more efficient, if they only cover certain segments of the network, with instances in different manageable parts of the network. As load varies, the same may be true for other services, such as mobility management or Authentication, Authorization and Accounting (AAA). Furthermore, multiple instances of management plane services could manage different regions of a network in federation. While connectivity between regions needs to be dependable, the regions also need to be operable on their own. The need to handle the changing topologies of nomadic, reconfigurable and non-terrestrial networks as well as increased need for dependability provide yet another challenge to the control plane network. Only with a zero-touch control plane fabric supplied by KIRA and the converged organic RAN-Core can the 6G control plane function efficiently in the geographically distributed in-network cloud continuum in a dependable manner. Because the organic, converged RAN-Core control plane follows a cleaner service pattern, it can be scaled better across the network and KIRA can ensure control plane connectivity even during disruptions and reconfigurations without human intervention.

XI. CONCLUSION

Programmability of network infrastructures plays a pivotal role in the current and future global communications networks. This is especially true in the context of 6G networks that are going to be very dynamic (e.g., due to NTNs, nomadic networks and Networks-in-Network) and require higher flexibility. The Open6GHub consortium has been at the forefront of research in this domain. In this article, we presented the latest research results towards programmable infrastructures for 6G from the project, demonstrating

- Advancements for programmable RANs by providing several building blocks such as FutureSDR, IPEC and HELIX to support hardware-based solutions.
- A scalable hardware transmission buffer design to cope with high data rates of 6G while achieving low latencies.
- An AI-driven protocol synthesis framework to optimize protocol behavior such as medium access.
- New automated and ML-based solutions to optimize traffic back-hauling.
- Organic 6G control plane services based on KIRA as scalable and resilient Control Plane Fabric as well as an organic core control plane on top.
- The proposed architecture also enables an Organic 6G RAN-Core Continuum.
- The effects of live migration when core functions were realized as VNFs.
- Insights into organic network VNF placement optimization.
- A deeper understanding of the interactions between fixed and nomadic networks, as well as between networks in networks.
- Logical and physical reconfiguration techniques that allow the network to change on-demand.

This work paves the way for the development of programmable infrastructures for 6G and beyond. To this end, we have provided an end-to-end architecture explaining the relationships between these and existing technologies. The architecture helps understand the complexity of future networks. The flexibility of the programmable 6G infrastructure has great potential, but effective MANO of the various elements will require a clean architecture with well-defined interfaces. What we have provided is a first step toward this architecture that brings together the different layers.

Although we have demonstrated these technologies in various scenarios, a complete end-to-end demonstrator is yet to be created. This would be important to prove the overall architecture but will require additional integration with third party components. Enabling programmability at this granularity increases the attack surface for malicious actors. The security and safety consequences need to be considered when moving towards real product implementations. Our perspective in this article focuses on 6G, i.e., 3GPP technologies, but integration with other network technologies needs to be understood as well and requires further work.

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