DYNAMIC INFRASTRUCTURE-AS-A-SERVICE: A KEY PARADIGM FOR 6G NETWORKS AND APPLICATION TO MARITIME COMMUNICATIONS

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Abstract – *Although, the advent of the fifth Generation (5G) of communication networks has introduced the technology enablers and system capability to support a large number of devices, and highly-demanding services, as well as ultra-low latency and high reliability, enhancements to the current systems will not suffice for future generation networks. Instead, a disruptive communication paradigm needs to be introduced that will ultimately enable the radical evolution of the current systems to a new ones, capable of self-aggregating extraordinary connectivity and computing capabilities in a seamless manner. To this end, sixth Generation (6G) networks should be able to seamlessly integrate and release, in a dynamic manner, heterogeneous types of resources, such as diverse types of network entities/nodes with nomadic, relaying, and multi-tenancy capabilities, which can enable demand-driven service provisioning, coverage extension, increased network capacity, and reduced energy consumption. This paper presents a novel networking paradigm towards Infrastructure-as-a-Service (IaaS), which introduces a disruptive and dynamic network infrastructure management and service orchestration mechanism, including nomadic networks and Artificial Intelligence (AI)-aware networking approaches for seamless and dynamic management of diverse network resources. In order to emphasize the compelling potential of the proposed paradigm, we detail its application to maritime communication networks, while identifying this use case as a key driver for the proposed dynamic IaaS concept.*

Keywords – 6G, AI-aware networking, beyond 5G, maritime communications, nomadic networks

1. INTRODUCTION

The latest advancements towards the fifth Generation (5G) of communication networks during the last few years have introduced several novel concepts and technology enablers that have broaden the capabilities of the network, primarily in terms of flexibility, capacity and end-to-end latency. In the context of these enablers, we highlight the technologies of Software Defined Networking (SDN), Network Function Virtualization (NFV), millimeter-Wave (mmWave) communications, massive Multiple-Input Multiple-Output (MIMO) systems, and network slicing [1][2][3]. As indicated by ITU in the respective Network 2030 White Paper [4], novel communication services with extreme requirements, such as holographic-type communications [5] and tactile Internet, are expected to emerge during the evolution towards the next generation of wireless and mobile systems beyond 5G. Numerous additional visionary use cases have been also proposed [6], such as Augmented Reality (AR), cooperative robotics (also referred to as cobots), and holographic calls.

As of today, the evolution towards 5G network technology largely relied on the exploitation of those technologies, which enabled flexibility on the control planes, versatility, and innovative business models. The 5G telecommunications markets will continue to be largely shaped by Mobile Network Operators (MNOs), whose business is structured around mass service provisioning with high advance investments in infrastructure and typically long-term licenses granted by the regulators. Nonetheless, the service delivery model is being transformed from an MNO-centric system into a more dynamic model, with decentralized service nodes at the edge of the network. According to the same white paper by ITU [4], the coexistence of heterogeneous network infrastructures and resources is one of the cornerstones. Densification of distributed edges and space communications integration with mobile and wireless communications are further examples.

Network densification will imply high CAPEX and OPEX for the infrastructure providers, unless a disruptive paradigm is introduced, which targets exploiting all available infrastructure and communication resources. This will minimize the costs required for extending the legacy infrastructure, while it will also accelerate the evolution to the envisioned ultra-dense network deployments and ultimately the cell-free paradigm. The above items call for a very versatile, pervasive, and autonomic resource control framework, which must be capable of maintaining the controllability of all available resource components regardless of their nature, the resulting network topologies, densities, usage loads, and fluctuations.

The 5G Infrastructure Association (5GIA) [7] in its recent vision for the sixth Generation (6G) network ecosystem foresees that in the next system generation, the infrastructure used by the mobile telecommunications systems will be provided on a a flexible and on-demand mode of operation. Future telecommunication infrastructures are expected to be a "resource pool," as a virtual infrastructure that will be allocated across the administrative boundaries of independent operating owners of resources. Ultra-dynamic infrastructure components are expected to include (i) physical devices with heterogeneous communication and computational capabilities and life spans (e.g., battery-driven and eco-powered) (ii) mobile or fixed, Public Network (PN) and/or even Non-Public Network (NPN) resources (e.g., terrestrial, satellite, train-mounted base stations, connected vehicles, etc.); (iii) virtual appliances running on physical devices, characterized by a sudden appearance or disappearance in dense clusters and, potentially, in high numbers of instances; (iv) services consumed by third parties (e.g., leased lines, transport services, etc.). Particularly, with regard to NPNs' exploitation in a dynamic manner, as part of the public network, the 5G Alliance for Connected Industries and Automation (5G-ACIA) [8] identifies two main scenarios for NPN-PN interworking, i.e., a) shared radio access network, in which the NPN and the public network share part of the radio access network, while other network functions remain segregated, and ii) shared radio access network and control plane.

A plethora of use cases and vertical industries, which rely upon the technologies and enablers introduced in 5G systems, have already realized a radical evolution towards the flexibility, capacity, and efficiency increase of their diverse operations. Nevertheless, one of the vertical domains, which still remains untapped is the maritime sector [9]. The maritime domain provides a very challenging use case [10][11]: The sea environment is characterized by very low network coverage and sparse network nodes density. Moreover, specific characteristics imposed by the sea environment i.e., signal propagation issues due to sea surface reflection, fading, time delay, etc. make several of the current terrestrial communication enablers inadequate for efficiently addressing such characteristics.

Currently, satellite communications is the only reliable way to get connectivity services on board of ships, outside the 5 nautical miles limit [12]. However, the limited provided service's achieved data rate, latency, and limited reliability make it difficult for the maritime ecosystem to fully adopt it and go one step further, towards 5G use cases and services. NetWorld 2020 [13] identified satellite-based communication, as one of the key enablers towards the Next Generation of Internet (NGI), discussing a number of potential enablers towards their evolution and integration in the 5G ecosystem. Thus, it becomes obvious that a novel networking paradigm, that will exploit flexible network management and service orchestration techniques, integrating also satellites as nomadic relay nodes with complementing communication resources, can potentially provide a holistic solution that will enable 5G communications in the maritime domain, leading to a plethora of novel business cases for maritime domain stakeholders, Internet service providers, as well as third party infrastructure providers.

To address the aforementioned characteristics, 3GPP in Release 16 [14][15] identified the maritime aspects related to ship-to-ship, ship-to-shore and intra-ship communications as important requirements for the evolution towards the next system generation. Starting from the maritime use case, 6G baseline architectures could enable the coexistence of an abundance of networking options. For 5G evolution, there is a growing need for enabling transparent dynamic and on-demand deployability. The networking or connectivity infrastructure for future vertical domains may be offered by domain specific stakeholders or infrastructure providers. To this end, already a set of Standardization Developing Organizations (SDOs), mainly 3GPP but also ETSI NFV, ETSI MEC and IETF among others, have produced the first set of specifications for the 5G architecture [16][17], as well as for the orchestration and management [18] of the various network slices [19].

To this end, it gradually becomes evident that conventional enhancements to the current system will not suffice in order to meet the ultra-challenging requirements that have already begun being formulated towards 6G; instead, a novel and disruptive communication paradigm must be introduced, that will ultimately enable the radical evolution of the current system to a new one, with inherent Artificial Intelligence (AI) capabilities that will enable the network to seamlessly self-aggregate and manage extraordinary connectivity and computing resources from diverse network entities and among numerous tenants, infrastructure, and/or service providers.

6G networks will comprise heterogeneous node types, with diverse capabilities and resource availability for serving different connectivity and computational requirements of the network. An example is Unmanned Aerial Vehicle (UAV) nodes, which can serve both as aerial base stations, as well as User Equipment (UE) [20] due to their flexibility and ability for Line-of-Sight (LoS) communications, and drone-BSs that can provide reliable wireless connectivity during disasters and temporary events. Drones can also act as UEs (i.e., cellular-connected drone-UEs) that must connect to a wireless network so as to operate.

At the same time, the heterogeneous nature of network services, along with the need for ubiquitous access, calls for cell-less architectural paradigms, based on the tight integration of different communication technologies, both separately for access and backhaul, as well as for advanced access-backhaul integration [21][22]. The massive data rates of 6G systems will essentially require a considerable increase in the backhaul capacity. The higher density of the heterogeneous access points will need backhaul connectivity to their neighbors and the core network. The huge capacity of 6G technologies can thus be exploited for self- backhauling solutions, where the radios in the base stations provide both access and backhaul. While a similar option is already being considered for 5G networks, the scale of 6G deployments will introduce new challenges and opportunities, e.g., as the networks will need higher autonomous configuration capabilities.

Nevertheless, open challenges, in dynamic backhauling, multi-hop connectivity, as well as nomadic and relaying aspects are of high priority towards providing several of the aforementioned disruptive network capabilities and are not still close to being adequately addressed. Nomadic and advanced Relay Node (RN) connectivity systems and schemes (e.g., conventional RNs, RNS with metasurface antennas [23], and passive metasurface-based tunable reflectors [24]) are expected to play a significant role for meeting the 5G use case requirements; however, the operators are currently using their own RNs, which are deployed after careful network planning. There are already proposals to use nomadic nodes as candidate relays, but even in this case the RNs are used when the vehicles are static [25]. The RN technology in 3GPP [26] is still in an immature state, i.e., as also identified in the latest 3GPP specifications [14] there is no provision for multi-tenancy or flexible network slicing capabilities.

One of the most promising, still at a very premature stage, use cases, which highlights several of the aforementioned gaps is maritime communications with its related applications [15]. This article introduces a novel disruptive 6G network paradigm that is particularly showcased via focusing on the challenging maritime domain-related use cases. The proposed framework introduces a novel architecture that highlights the concept of ships as micro-operators, towards a dynamic and multi-hop approach providing dynamic Infrastructure-as-a-Service (IaaS). This core concept is federated by a set of networking, communication, and computing enablers that introduce added value capabilities and business models into the current operations of the maritime vertical domain and beyond.

The rest of the document is organized as follows (c.f., Fig. 1): Section 2 presents prior existing efforts from the literature with regard to dynamic infrastructure and connectivity topics, as well as solutions from the maritime domain. Section 3 presents the maritime communications use case, along with its key requirements, challenges and identifed gaps in the current systems. Then, Section 4 presents the proposed concept and high-level architecture towards addressing ultra-challenging domains such as the maritime, while it also provides a detailed overview of the main technical enablers of the envisioned networking paradigm. Section 5 discusses open issues and next challenges to be addressed towards the described vision, while Section 6 concludes the document.

Fig. 1 provides a representation of the paper's structure and main topics.

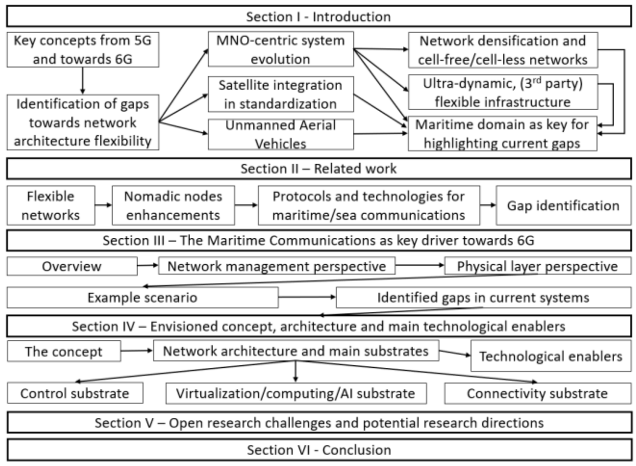

Fig. 1 – Structure of the paper

2. RELATED WORK

Discussions around agile network deployments and flexible management of nodes has been around for some time, since the previous generation of wireless and mobile systems. Gran et al. [27] proposed a novel Wireless Infrastructure-as-a-service (WIaaS) paradigm, which enables mobile virtual network operators to provide distinguished services to their subscribed users, while sharing a common physical infrastructure. The proposed concept builds upon wireless resource virtualization, ultimately targeting wireless resource slicing upon software-defined architectures. This work focuses on a hypervisor-coordinated resource allocation problem, without discussing though the dynamic integration/release of connectivity resources, along with the agile service orchestration requirements that this methodology brings.

Bulakci et al. [28] investigated moving networks as a promising enhancement for 5G systems to enable flexible network deployment, via the management and orchestration of nomadic-nodes-oriented resources, which can enable demand-driven service provisioning. They studied the on-the-fly network planning and energy-aware optimization use cases, via focusing on channel model and energy consumption problems respectively.

Ren et al. in [29] and [30] presented an optimization framework for energy savings in a dynamic nomadic relay node environment. With the goal of enhancing energy efficiency in mind, they formulated an optimization problem that takes into account wireless backhaul links for the nomadic RNs.

As highlighted in the beginning of this work, the key use case that will be showcased as one of the most representative ones for the introduction of the envisioned paradigm is maritime-domain wireless communications. Besides the above presented efforts focusing on dynamic infrastructure (-as-a-service), several proposals have been so far presented in the literature that focus on maritime communication aspects exploiting a variety of either commercial or novel and research-oriented technology enablers.

In [31], a revised IEEE 802.16e (WiMAX) protocol was proposed in order to cope with signal propagation aspects and challenges due to sea surface reflection, fading, time delay, Doppler shift, sea state, and rocking motion of ships. In [11], the authors presented the TRITON project, which developed a high-speed and low-cost maritime communications system comprising a wireless mesh network, based also on the IEEE 802.16 standard. This work investigated the effects of the sea surface movement and identified the optimal mechanisms and protocols in different layers of the network for coping with the related challenges. The work in [32] focuses on the routing challenges that result from the maritime environment characteristics and the ship mobility patters. In particular, the authors proposed a modified version of the AdHoc On-Demand Multiple Path Distance Vector (AOMDV) routing protocol that provides a route recovery mechanism when a link breaks in an active route to reduce lost packets. Hoyhtya et al. in [33] presented a survey on connectivity for autonomous ships and related challenges, along with a number of use cases such as: remotely controlled shipping, multi-hop connectivity, and in-ship sensor deployments. In [34], Kim et al. presented an implementation of an LTE-WLAN maritime heterogeneous relay network. The work in [35] focused on the physical layer aspects of Ship Ad-hoc Networks (SANET) based on 3GPP LTE and IEEE 802.11p specifications. Park et al. in [10] present a coverage solution for LTE-based maritime systems, along with an ocean propagation loss model. The work in [36] presents an LTE terminal for operation in the maritime environment. The main proposed feature was an antenna system with stabilization features in order to provide a coverage area of at least 10 nautical miles. Last but not least, Xu in [37] proposed a user-centric communications architecture based on distributed land-based antennas.

As can be inferred, numerous works have already identified the challenges related to maritime communications and the requirements towards achieving broadband services for on-board users, as well as enabling the digitization of in-ship operations. Most of the presented efforts study legacy communication technologies, such as WiMAX and LTE, while they either focus on physical-layer-related challenges and describe specific hardware systems, or propose scheduling/network-management-related optimizations of protocols in layers 2 and 3, respectively. The proposed networking paradigm in this paper attempts to go one step further and address the maritime communications challenge in a holistic manner. It brings into the discussion the challenges and enablers related to the evolved 5G and 6G networks, such as network slicing, as well as multi-operator and multi-vendor related aspects, while discussing signal propagation solutions from the state of the art in mmWave communications. The envisioned networking paradigm introduces a holistic architecture, comprising native AI design considerations, agile management and orchestration for dynamic backhauling and multi-hop networking, blockchain-enabled approaches for network slice management, and adaptive Radio Access Network (RAN) features via a disruptive IaaS concept.

3. THE MARITIME COMMUNICATIONS AS A KEY DRIVER TOWARDS 6G

The maritime domain provides a very challenging use case. The sea environment is characterized by very low network coverage, sparse network nodes density, as well as in principle mobile, and opportunistically available (as in the case of moving ships and/or mobile sea platforms). Additional challenges, such as the specific characteristics imposed by the sea environment that make several of the current terrestrial communication enablers inadequate for addressing 6G requirements, especially when taking into account issues related to signal propagation issues due to the sea surface reflection, fading and time delay, make the specific use case ultra-challenging for the forthcoming 6G requirements. Both from the network, as well as from the physical, layer-related perspectives, it becomes thus obvious that the current system is inadequate to provide the envisioned seamless service provision.

From the network management perspective, and towards addressing the network coverage, as well as capacity, limitations, the 6G system should integrate diverse types of nodes already available in the maritime environment, such as the ships or floating platforms, by also extending their current capabilities with access, as well as edge computing features. Those nodes should be able to provide high-capacity access, e.g., via massive MIMO antennas, intelligent reconfigurable surfaces, etc., while processing resources that could contribute in the minimization of the end-to-end latency of demanding services. This would introduce a maritime, multiaccess edge computing paradigm, capable of offering extreme processing capabilities at the far edge of the network, for numerous related services, without having the need to relay traffic to the terrestrial segments of the network.

In cases however, that the traffic should be relayed to those terrestrial segments, e.g., for reaching specific terrestrial application servers, besides the existing maritime domain nodes, satellite, as well as airborne-based (UAVs, ballons, high altitude platforms – HAPS, etc) network elements will be part of the end-to-end communication for relaying those communication parts.

To this end, advanced, agile mechanisms are required, capable of managing dynamic network infrastructure (i.e., the ships acting as temporary nomadic and/or relay nodes) that do not always belong to a specific mobile network operator, and should be mostly considered as NPN infrastructure segments. This infrastructure can be provided by a maritime company/ship owner as an IaaS. The mobility of the ships adds more flexibility, as well as complexity, to the overall infrastructure management, as dynamic network formations will be asking for proactive resource orhestration and intelligent resource allocation.

The latter requirements in turn impose the need of extending several of the current functionalities of the network management plane, related to the association/release of network RNs in a low-latency manner, efficient and dynamic service orchestration, and end-to-end security mechanisms supporting the newly created network links. In addition, flexible network-slicing-enabled resource allocation schemes are required, which need to be capable of dynamically reformulating in near-real time existing network slices according to the newly introduced infrastructure and respective requirements.

Disruptive advancements in the lower layers of the network, such as advanced sensing and channel estimation, the exploitation of intelligent reconfigurable surfaces mounted on aerial network elements for enabling line-of-sight signal propagation, link adaptation techniques combined with AI-assisted direction estimation and beam management, as well as management of hybrid optical wireless communication solutions for inter-satellite, as well satellite-to-airborne-to-maritime links will be key to this transformation.

Fig. 2 – An example 6G maritime scenario capitalizing on the proposed dynamic IaaS networking concept

Fig. 2 illustrates an example use case near the port of a terrestrial area, primarily highlighting the integration and dynamic access/backhauling switching between satellite/airborne/maritime and terrestrial wireless communication technologies (e.g., mmWave or subTHz), the secure and flexible interconnection between different MNOs' network domains co-exploiting the floating platforms access base stations, as well as the network-slicing-enabled relaying capability of such nodes for supporting such a multi-MNO scenario.

Such a use case would involve the adoption of moving ships mounted with 5G NR, and beyond, elements (e.g., massive MIMO, large HBF antennas for mmWave and subTHz, and reconfigurable intelligent surfaces), acting as dynamic connectivity nodes with nomadic and relaying capabilities. In the illustrated example of Fig. 2, two MNOs (red and blue colors) are operating in the wider port area of a city, on top of both proprietary as well as third party infrastructure (access network elements in black, yellow and green color). The ships may provide multiple Radio Access Technologies (RAT) interfaces to the end users on board (i.e., 5G NR/LTE/Wi-Fi). Besides the ships, which are considered the core infrastructure of the proposed use case, complementary infrastructure is envisioned that can be exploited towards better network coverage and connectivity reference points. A number of static floating platforms (e.g., existing decommissioned ships) are deployed, acting as complementary RNs in a multi-hop backhaul network operation type.

A plethora of diverse network service types and respective requirements could coexist in such an environment that requires flexible and intelligent management of traffic flows, dynamic switching and splitting depending on real-time channel conditions for each one of the available access/backhaul endpoints, as well as runtime-based monitoring and resource control.

We envision an evolution of the existing 5G enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communication (URLLC), and massive Machine Type Communication (mMTC) service types to more complex groups of services with combined requirements, while in some cases also accompanied by Time Sensitive Networking (TSN) requirements for the wireless domain (Fig. 3).

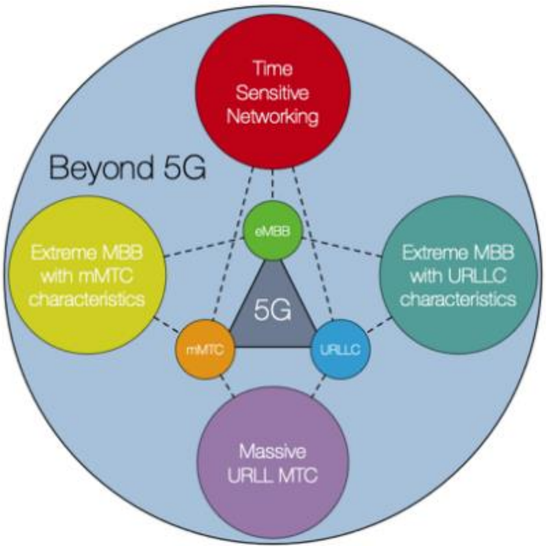

Fig. 3 – Service evolution beyond 5G

Significant gaps are currently identified in today's networks, whereas standardization efforts are targetting to gradually address them. Ultra-high network flexibility, maritime/airborne infrastructure programmability and controllability towards seamless, secure and ultra-low latency integration and release of (third party) infrastructure, management and service-agnostic orchestration of related connectitivy resources, including agile mechanisms for low latency association/release of moving relay nodes and/or NPNs, multi-tenant, multi-slice, and multi-operator support of network relays are some of the most representatitve ones. Moreover, robust and AI-assisted beam management schemes for coping with the challenging sea surface environment, as well as flexible, software-enabled, and virtualized resource (dis)aggregation via the functional split of RAN functionalities are some of the key missing enablers, which we highlight. The envisioned concept targets extending several of the state-of-the-art functionalities of the baseline 5G architecture through the creation of novel business models, both for existing 5G network-related stakeholders, as well as new market players from the vertical domain. The following section provides a detailed discussion on the enablers towards adressing the aforementioned open challenges and gaps, while it also gives a conceptual overview of the envisioned architecture.

4. CONCEPT, ARCHITECTURE, AND MAIN TECHNOLOGICAL ENABLERS

4.1 Concept

One of the primary principles introduced towards the envisioned concept, is the seamless integration of diverse satellite, airborne and maritime elements as network nodes with multiple access and backhaul connectivity capabilities, in the context of the cell-free paradigm. Fig. 4 introduces the Ubiquitous Connectivity Fabric (UCF), one of the key architectural concepts of the proposed networking paradigm.

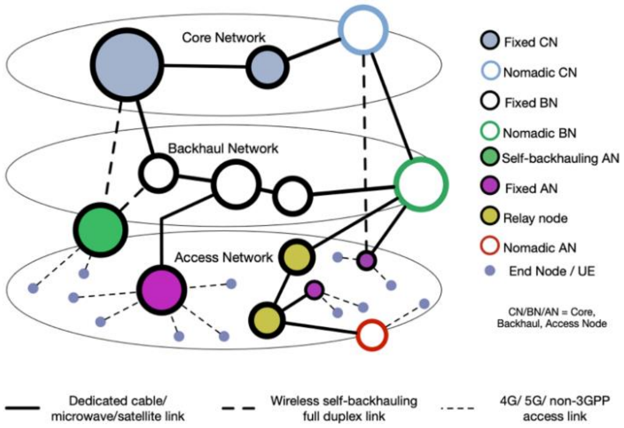

Fig. 4 – The proposed Ubiquitous Connectivity Fabric (UCF) including various forms of nodes and diverse communication links

Nomadic nodes with integrated access, as well as backhaul (IAB) functionality (i.e., 5G Core, 5G New Radio (NR), satellite nodes, RNs, reconfigurable intelligent surfaces etc.) are introduced for all network segments (i.e., access, backhaul, and core) in order to enable demand-driven service provisioning, increased network capacity, dynamical extention of network coverage, and energy consumption reduction (e.g., in the case of nomadic core nodes and distributed core network functions' support).

One of the key innovations introduced by the envisioned paradigm, compared to the existing concept of nomadic nodes, is the fact that such nodes do not need to belong to any operator and are capable of providing relaying, as well as multi-tenancy capabilities. This unique feature will ultimately lead to a multi-tenant and multi-domain meshed system, which will be flexibly integrating connectivity resources in a common pool available for all tenants, thus, further federating the overall smart connectivity concept. Additionally, the integrated access and backhaul capabilities, recently being defined in the context of 5G but for static nodes so far, will largely facilitate the connectivity options for sparse networking environments, such as the maritime one presented earlier.

Towards exploiting those heterogeneous resources, the different capabilities of the individual nodes must be defined and characterized in a formalized manner, in terms of connectivity/communication, localization/positioning, computing, as well as storage resources. Particularly, in relation to the connectivity/communication resources, extensions to the existing RRC procedures are required, in order to enable the network to identify in an automated and seamless manner the available node capabilities and resources, and perform dynamic resource brokerage, in terms of management, control and orchestration.

4.2 Network architecture

The envisioned system leverages the already-established enablers and technologies by the industry and the standardization organizations (primarily, 3GPP and ETSI), such as the management and service orchestration framework, the network slicing technology, the SDN-enabled control plane, and the Operation Support System (OSS), etc.; however, the main objective of this section is to highlight the disruptive elements, i.e., the ones that we believe are the key for ultimately enabling the envisioned network paradigm for addressing challenging environments, such as the maritime. We illustrate the respective innovations from three key different perspectives, namely the control, the virtualization/computing/AI, and the connectivity/communication substrates (Fig. 5).

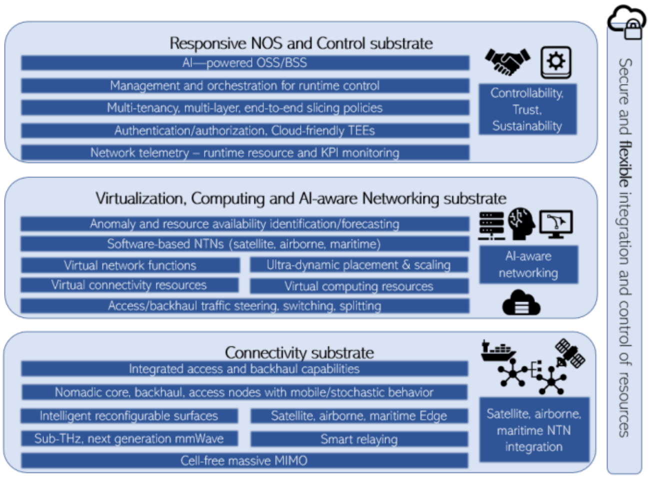

Fig. 5 – The conceptual network architecture with the three horizontal substrates and key enabling technologies

In more detail:

a) The *Responsive Network Operating System (NOS) and Control Substrate* comprises the primary control operations, i.e., the end-to-end management and orchestration framework, the multilayer slicing management (both from the network, as well as from the business and Service Level Agreement (SLA) perspectives) and respective resource allocation policies, the SDN layer control policies framework, the holistic security and trust mechanisms in the integration of connectivity and computing resources and environments, the real-time monitoring mechanisms for seamless inter-domain resource allocation and dynamic IaaS enablement, as well as the evolved Operation and Business Support Systems (OSS/BSS) with AI-powered capabilities for increased flexibility and robustness. The multilayer slicing module is responsible for all the business operations, as well as the high-level policies towards the control plane functionality of the overall system, related to resource allocation as well as SLA modeling and control, towards the isolation, virtualization, and multi-domain management of resources, especially between multiple service providers. Authentication/authorization mechanisms for agile third party infrastructure integration and release are part of this substrate.

The envisioned paradigm introduces advanced network telemetry and runtime-based resource monitoring for low-latency resource control. The proposed system introduces an evolution of the current Trusted Execution Environments (TEEs) towards more "cloud-friendly" capabilities, in order to successfully cope with essential features of cloud deployments, such as replication and migration. Towards the same direction, a refined trust model of TEEs must be introduced: as of now, the TEE application assumes a completely trusted hardware; what meaningful security properties can be achieved if the hardware is subverted, should also be investigated.

b) The *Virtualization, Computing and AI-aware Networking (VCAIN) substrate* consists of the abstracted resource pool of virtualized network (computing or communication) resources and functions (i.e., Virtual Network Functions (VNFs)), the decision-making frameworks and AI/ML algorithms for resource allocation, as well as the respective northbound and southbound interfaces towards the control and physical management agents, respectively. Additionally, the specific substrate encompasses the AI-aware networking framework, which focuses on introducing a disruptive approach and evolution of the current AI network operations via considering the AI operations as a structural component of the network itself. This will require, in turn, a radical evolution from the architectural prespective, in order to enable a seamless and efficient operation.

Besides the AI-powered network optimizations, as those have already been shaped in the evolution towards the 5G system with various optimizations in the resource allocation, mobility management, user-cell association, etc. concepts, the proposed system introduces the concept of AI-aware networking, i.e., the evolution of the system towards a self-aware, intelligent, and flexible platform that will exploit on the one hand AI for networking, as with previous efforts, but at the same time will ensure that the intelligence plane, related signaling procedures, required interfaces, trustworthiness of AI-related decision-making processes, etc. are part of the overall design of the system, placing AI as an inherent component of the system that participates in all operations, in a similar manner to the user and data plane procedures. This paradigm aims to bridge the gap between the network communication protocols and the AI/ML algorithmic design by identifying common requirements and limitations that result from the two domains. Such examples comprise considering different dimensionality reduction or data encoding techniques for limited computing capabilities devices, such as Internet of Things (IoT) nodes, adaptive gradient aggregation for improved resilience, or joint channel coding and image compression techniques in noisy wireless environments. In this way, the AI-enabled edge becomes also one of the cornerstones of the proposed paradigm and will be further discussed in the following sequel.

Several key enablers, several of which exploit the AI-aware networking framework outputs, are also part of the VCAIN substrate, including Access Traffic Steering, Switching, Spliting (ATSSS) mechanisms, handover optimization schemes, as well as the required interfaces and logical modules, which coordinate the core of the system with AI-enabled edge, which is described in greater detail in the next subsection.

c) Finally, *the Connectivity Substrate* comprises the physical infrastructure and physical network functions, the nomadic Core Nodes (CN), Backhaul Nodes (BN), and Access Nodes (AN) (including sub-TeraHertz (subTHz) and mmWave radio interface capabilities), the dynamic (satellite) integrated access and backhauling management, along with the related infrastructure and physical links. In the context of this substrate, the solutions for ubiquitous local access network support will be designed based on a nomadic dynamic infrastructure, while focusing on the flexible deployment of very large numbers of ANs. In the connectivity substrate, the heterogeneous local access network support can be integrated considering THz front-haul, satellite direct connectivity, as well as 5G evolution and 6G access networks. This will provide a comprehensive solution for potential connectivity to the system's nomadic nodes.

Another key enabler residing in the connectivity substrate is the dynamic (integrated access/)backhauling support. In order to support this novel functionality, a comprehensive solution should be developed for the nomadic nodes to address the heterogeneous backhaul usage, also acting as a fundamental piece in the interconnection between the nomadic nodes and the CN entities of the system.

Last but not least, the connectivity substrate involves a set of novel techniques and mechanisms for differentiating the coexisting nomadic node services for both the functional part, as well as for the support for the multi-tenancy operation. This can be accomplished through enabling the ubiquitous communication to handle also the use case requirements in a differentiated manner. More details regarding the specific enabler are provided in the next subsection.

4.3 Technological enablers

4.3.1 Agile management and transparent provision of connectivity IaaS

The envisioned architecture introduces the ability of the network to transparently integrate on-demand network nodes, resources, and services. This needs to be realized in a highly flexible manner, taking into account the network's dynamics, and via applying novel end-to-end orchestration and multilevel slicing capabilities on the underlying infrastructure. The detailed procedure of the seamless integration of third party infrastructure nodes is showcased in the context of the maritime domain, but is easily generalized for all vertical domains, which comprise nodes with mobility or nomadic characteristics, such as the automotive domain.

Building upon the 3GPP terminology on the RN technology [26] and focusing on the maritime domain as one of the most challenging environments for seamless connectivity, the envisioned system assumes that specifically from the UE's point of view, Maritime Nomadic Nodes (MMNs) have identical capabilities and behavior with any other 5G NR gNodeB (gNB)/Evolved NodeB (eNB). The gNB/eNB, in which RN capabilities are also featured, is called the Maritime Donor eNB (MDeNB) and may be part of the ship/floating platform infrastructure. Accordingly, the MDeNB provider may be the ship owner or any other third party infrastructure provider. The MDeNB must be informed about the MMNs that are located inside its range and are responsible to provide proxy functionality to its interfaces with the rest of the network infrastructure, e.g., the core network. In order to set up the connection and forwarding capabilities between the MDeNB and the MMN, the MMN will be handled as a UE from the point of view of the MDeNB.

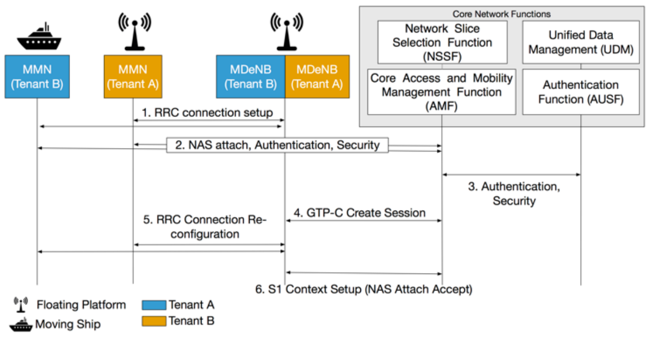

Fig. 6 – MMN attach procedure for multiple tenants and/or infrastructure providers

The proposed concept is schematically described in Fig. 6. The RRC Connection Setup (RRC-CS) procedure (Step 1), in line with the standard 3GPP's RRC-RC, is realized via forwarding the MNNs' requests and responses via the respective multi-tenant MDeNB node. The MNNs realize Non-Access Stratum (NAS) attachment procedures, along with Authentication (Step 2), via the Access and Mobility Function (AMF). The required authentication and related security-driven operations are complemented by the Authentication Function (AUSF) (Step 3) in order to trustfully encompass the newly-integrated infrastructure in the required end-to-end orchestration lifecycles via a secure connection set-up. The respective GTP-C session is created (Step 4), along with the respective RRC Connection Reconfiguration (Step 5) and S1 interface context set-up (Step 6). The MMN terminates the S1 and X2. The MDeNB provides S1 and X2 proxy functionality between the MMN and other network nodes (other eNBs, MMEs and serving gateways). The S1 and X2 proxy functionality includes passing UE-dedicated S1 and X2 signaling messages as well as GTP data packets between the S1 and X2 interfaces associated with the MMN and the S1 and X2 interfaces associated with other network nodes. Due to the proxy functionality, the MDeNB appears as an MME (for S1-MME), an eNB (for X2) and an S-GW (for S1-U) to the multi-tenants' MMNs.

Its main novelty with regard to the existing relaying mechanisms lies on: a) the multiple slice support of the MMNs; and b) the multi-tenancy aspect. The network nodes may belong to any MNO, or they may be provided by a third party infrastructure provider, such as a port authority that may deploy a number of gNBs, or a ship owner that may deploy a number of connectivity RNs on the ship towards enabling network extension over the sea. The proposed concept considers a multi-operator and multi-domain environment with multiple slices being served by common RAN elements. It is based on adaptive RAN sharing techniques, spanning from fully isolated to mingled slicing approaches.

This enabler focuses on the dynamic network coverage/service extension, as well as the flexible planning and transparent integration and management of RNs, which particularly belong to any third party network equipment providers. To this end, the respective enhancements are proposed for the existing 3GPP model roles for network slicing management; see Fig. 7. The illustrated enhancement uses the example of a nomadic node ship as a micro-operator, inspired by the maritime use case, which will be discussed in more detail in the following section.

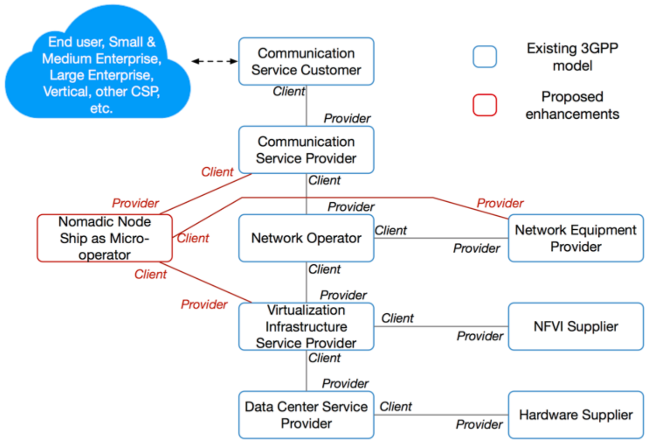

Fig. 7 – Enhanced interconnected 3GPP model roles for network slicing management [38]

Fig. 7 provides a tailored design of the *Provider* – *Client* roles in the network slicing management framework, as described by the relevant 3GPP specification [38]. Towards realising the afore-presented concept, the micro-operator role is introduced, which is directly associated to the communications service provider, as well as to the network equipment provider and virtualization infrastructure service provider roles. A second entity, besides the network operator, is thus contributing its resources in the so-called micro-domains (such as the maritime segments), serving as a complementary stakeholder in the current business landscape.

One of the most challenging aspects that the envisioned paradigm introduces relates to the seamless and efficient service orchestration, particularly for the cases in which dynamic infrastructure is involved. This could imply the participation of nomadic nodes, contributing physical and/or virtual resources to the end-to-end network service, or private network domains, which temporarily expose their resources for service orchestration optimization purposes. Network service decomposition and optimal placement/migration of network services is required in such a dynamic federated infrastructure, that will proactively manage and allocate the required communication and/or computational resources from diverse participating entities. A key enabler towards seamless orchestration for such dynamic environments is ML/AI-driven closed-loop automation and SLA control [39].

4.3.2 AI-aware networking and AI-enabled edge

The use of AI and data analytics to support the operation of 5G networks has lately emerged as a hot research topic [40], [41]. Several network procedures, ranging from AI-assisted service orchestration and efficient network slicing to intelligent resource allocation and mobility management approaches will rely upon (big) data analytics and AI models to provide a more robust and efficient network operation.

One of the key technical enablers is the AI-aware networking paradigm, which aims on the one hand to place AI and the respective *intelligence plane* as inherent components of the system that will be participating in the system design in a similar way to the user or data plane procedures; on the other hand to bridge the gap between the network communication protocols and the AI/ML algorithmic design. This will be realized by identifying common requirements and limitations that result from the two domains. Such examples could be considering different dimensionality reduction or data encoding techniques for limited computing capabilities devices (such as IoT nodes), adaptive gradient aggregation for improved resilience, or joint channel coding with image compression techniques in noisy wireless environments. The envisioned concept proposed the design and implementation of novel protocols and interfaces between the control plane (e.g., the network orchestrator) and the AI services running on top of the network.

To this end, new techniques need to be developed aiming approaches that can offer a holistic view of all network resources including communication, computational, and/or memory and storage, targeting to meet the requirements of AI applications, and to enable the flexible execution of AI applications. Additional considerations with regard to the requirements regarding abstractions, real-time capabilities, security, bandwidth, latency, and communication technology should be taken into consideration.

The AI-enabled edge, which exploits the AI-aware resources residing at the (far) edge of diverse network domains, is also a key enabler towards the enablement of the native AI paradigm that we envision. Federated/Distributed AI algorithms running at the edge of the network will enable a radical increase of resource exploitation, while it will boost the scalability of the AI-related decision-making, always placing data privacy and security on first priority. Integrating an AI-enabled edge into the envisioned AI platform passes through the development of highly distributed and heterogeneous architectures on AI-driven, VNF placement and service lifecycle management operations. Moreover, at the radio access and on the end devices, this task includes the design and implementation of novel distributed edge/UE/RAN-based AI VNFs, e.g., with UE profiling capabilities towards intelligent RAN resource management, traffic steering/splitting policies extraction, and dynamic service orchestration, such as distributed VNF placement and (auto)scaling.

On top of the above-presented enablers, the proposed architecture that we envision, employs a diverse set of AI algorithms such as deep learning approaches in order to optimize multi-slice resource allocation among multiple operators and network services, energy-efficient VNF placement, end-to-end service orchestration, as well as user-centric cell free networks via advanced access traffic steering and splitting. Forecasting capabilities and insights on the resource utilization, load, and cost, as well as energy consumption of the infrastructure equipment on per network slice/service level, UE and node mobility, network anomalies' detection, and security breaches, also tackling malicious behavior, as well as business constraints under consideration. Diverse data sets are required from different network segments towards processing and extracting such knowledge.

4.3.3 Advanced beam management and wireless channel tracking techniques

Besides the disruptive network management techniques that have been already discussed, a number of advanced Hybrid Beamforming (HBF) techniques are featured, for addressing the challenges related to the signal propagation over the sea environment. Efficient beam alignment and tracking design with HBF architectures at both the MRNs/base stations, as well as the UEs' side need to be available:

a) *Hierarchical/multilevel beam searching*: All communication ends employ beam codebooks including vectors (or beams) of different widths from which their analog precoders and combiners are obtained. Then, each communication pair searches in a ping pong fashion for the pair of an analog precoding matrix and an analog combining matrix meeting a predefined single performance objective or multiple performance objectives [42]. After finding the first pair satisfying the objective(s), the digital precoding and digital combining matrices are designed based the effective channel matrix.

b) *Beam searching aided by direction estimation and subspace tracking*: The goal of this direction is to initiate the beam searching process after each beam misalignment detection with a gross estimation of the spatial components of the wireless channel [43] . In this way, beam searching will start from beams that steer close to the actual directions of the channel's multipath. The estimation of the direction of the channel's spatial components, i.e., the angle of arrival and departure of each component, can be performed by: i) using dedicated direction-finding algorithms (e.g., Multiple Signal Classification (MUSIC), Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT), and its variations), which require in general calibrated antennas, although robust algorithms can be designed too; and ii) by estimating the channel covariance matrix and then eigendecomposing it, or directly applying a covariance subspace tracking algorithm.

c) *Compressed sensing channel estimation aided by direction estimation and/or subspace tracking*: This direction aims to apply compressed sensing channel estimation to a spatially reduced sampling space. Starting with a gross estimation of the spatial components of the channel, we may spatially sample the channel using beams from the available codebooks that are as close as possible to the actual directions of the multipath of the wireless channel [44]. In this way, the number of training beams will decrease resulting in a smaller measurements' matrix, thus, leading to reduced algorithmic complexity and a shorter beam alignment phase.

4.3.4 Flexible functional split, based on end-to-end resource (dis)aggregation

The SDN/NFV-driven control plane of the envisioned system enables hierarchical multilevel orchestration and management of the multilayer network, as well as computing and storage resources. Initiating from the NFV Management and Orchestration (NFV-MANO) principles, the envisioned system's core offers a complete management and resource orchestration system, comprising a VNF orchestrator, a VNF manager, a Virtualized Infrastructure Manager (VIM), as well as a cloud and transport SDN orchestrator. Orchestration capabilities are extended towards supporting the dynamic introduction and management of heterogeneous nomadic/relay maritime nodes, which may be simultaneously used by more than one MNO, or to nodes, which will be simultaneously serving more than one network slice.

The notion of network function segment, along with the microservices' concept [7], is considered as a key functional building block for the real-time aggregation and disaggrenation (in the form of automatic release) of connectivity, storage, and computing resources providing an operational bundle. Specific extensions are required in the current NFV MANO framework. This applies in particular to the VIM, which controls and manages the NFV infrastructure compute, storage, and network resources and must encompass resource management and security features in a connectivity substrate to dynamically package up a service/application with all the functional parts necessary for their deployment and operation.

5. OPEN RESEARCH CHALLENGES AND POTENTIAL RESEARCH DIRECTIONS

The proposed networking paradigm creates the incentives for addressing a whole new set of challenges for 6G use cases, and specifically the still unexploited domain of maritime wireless communications. However, several key questions and challenges remain open towards forthcoming research steps.

Firstly, it would be necessary to identify, which are the key elements required for the evolution of the 5G system into a flexible, software-based enabler, where dynamic and moving network nodes are stochastically introduced to the network as connectivity/relay nodes, without necessarily belonging to any operator. This would on the one hand require to introduce those orchestration software-driven mechanisms, which, on top of the virtualized infrastructure resources, will enable the monitoring and network control of the various connectivity elements in runtime, rather than the static configuration management elements procedures; respective events should be communicated towards the neighboring connectivity elements, as well as the virtualized network control, so that the seamless integration/release of those resources will take place in almost-real time and in a service-agnostic manner for the infrastructure.

Additionally, third party infrastructure (not belonging to any operator) will require the introduction of novel business models and operations, as well as well-defined interfaces, multi-tenancy capabilities and APIs. End-to-end slicing enablers to include communication and computing resources, potentially belonging to different stakeholders are also of the utmost importance for such infrastructure provision and orchestration, towards ensuring that the required QoS and resources in the access, backhaul and core parts of of the network can be seemleesly combined. To this end, AI-driven, runtime resource control is also crucial, as resource management in scenarios with high traffic/connectivity elements, belonging to different stakeholders, will be a frequent case. On top, towards ensuring AI transparency, fairness and unbiased resource allocation decision making processes, trustworthy and explainable AI-driven auditing layers should be integrated in the management and orchestration of the system.

Besides network control and orchestration, further research will be needed in the physical layer, in order to drive the mmWave, as well as sub-THz frequencies to flourish in such challenging environments. AI-powered, joint communication and sensing capabilities, as well as other beyond 5G & 6G enablers such as intelligent reconfigurable surfaces must be integrated in the system, with energy efficiency and network sustainability as top priority.

In terms of the overall architecture, the service-based approach adopted for the 5G systems have already introduced a first level of flexibility; virtualization is of the utmost significance to further extend the flexibility of the network, while the integration of open RAN capabilities and disaggregation techniques will further accelerate this flexibility trend. Cell-free network architectures will also be vital, along with advanced, smart combination of access and core network paths, dynamic traffic splitting and steering techniques over the numerous, coexisiting access networks for maximising resource utilization and ultimately performance for diverse services.

Identifying the actual key benefits, along with the involved complexity, from the infrastructure providers', network operators', service providers', and vertical industries' perspectives, will also be important for facilitating the collection and prioritization of key functional requirements of the various domains and translating them into specific sets of technical advancements of the current system architecture.

As several efforts from several standardization bodies and vertical industries have already begun addressing numerous related aspects, it is expected in the very near future a plethora of advancements towards this novel 6G connectivity paradigm will emerge.

6. CONCLUSION

This paper presented a novel networking paradigm, highlighting the IaaS as one of its key enablers. The envisioned concept introduces a disruptive and dynamic network infrastructure management and service orchestration framework, focusing on the considerable gains that nomadic networks and AI-aware networking approaches can bring towards seamless orchestration of heterogeneous, opportunistic connectivity and compute resources. Besides the network-related aspects, advanced, AI-enabled physical layer optimizations are introduced as well. In order to emphasize the compelling potential of the proposed paradigm, the envisioned system showcased its application to maritime communication networks, identifying it at the same time as a key driver for the next generation of wireless and mobile systems.

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