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6G Sub-Networks: From Use Cases and Requirements to Concept and Architecture

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ABSTRACT

The 6th generation of wireless mobile networks (6G) is envisioned to extend the capabilities of cellular communication networks into new dimensions, such as sensing, integration of artificial intelligence, and integration of other networking technologies. In addition, 6G is often described as the generation that will be the “Network of Networks” (NoN). One of the NoN building blocks is provisioning of local connectivity by so called 6G Sub-networks (SNs). Despite the fact that the term “Sub-networks for 6G” is already widely used, it still lacks a clear technical definition. This article aims to address this gap by providing contextualization and a description of the concept from various relevant perspectives such as legacy, autonomy, and topology. Moreover, a concept for an architecture is proposed, including Sub-networks, their interaction with associated user equipment, other Sub-networks and “Parent Networks” (PNs). These concepts are then mapped to a variety of use cases from relevant vertical domains, like vehicular Sub-networks, Sub-networks for collaborative and autonomous robots in factories, remote operation of aircrafts, airplane onboard systems and emergency services. Finally, a comparison of the described Sub-network concept with existing approaches in 3rd Generation Partnership Project (3GPP) is provided, stating similarities, differences, and future requirements for standardization.

INDEX TERMS 6G, Subnetworks, Wireless Technologies, Wireless communication, Wireless sensor networks, 5G mobile communication, Production, 3GPP, Industries, Network architecture, Reliability

I. INTRODUCTION

On the way towards definition of 6G, “Network of Networks” (NoN) is often described as one of the key properties of 6G [1]. One of the fundamental building blocks of NoN will be the introduction of efficient, highly performant, and resilient local communication.

The concept of 6G Sub-networks (SNs) is aimed at extending the capabilities of 5G to meet these specific needs. While SNs have been mentioned in various publications as a concept to enable highly application-specific, local, and high-performant wireless communication, it still lacks a clear technical definition and standardization requirements [1][2].

In many publications, description of the concept itself is still vague and does not yet allow to pinpoint what exactly is needed from a technical point of view [3]. E.g. in [1] the SN-concept is motivated based on physical propagation characteristics and use cases, but implementation assuming existing 5G architecture paradigms remains open. Similarly, [4] points out the potential of SNs, which can be integrated with existing cellular infrastructure, and provides simulation results for radio resource management approaches. Nevertheless, the aspect of SN-Architecture (i.e. which elements characterize a SN) and integration with larger networks, remain an open question. As a consequence, it is still rather hard to predict what would be needed from a standardization perspective. To distinguish the concept of SN from similar terms that exist in the history of 3GPP, e.g. femtocells or small cells, the aspect of autonomy needs to be mentioned here. Since cells are only part of the

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Radio Access Network (RAN), and do not comprise any part of the Core Network (CN), autonomous operation (e.g. for local connectivity) won't be possible, and SNs are conceptually different.

Thus, Sub-networks (SNs) conceptually differ from femtocells by offering a much higher degree of autonomy and application-specific flexibility, allowing for local processing and control even when disconnected from a Parent Network (PN), a capability not inherent in femtocells. Unlike femtocells, which are primarily fixed access points extending coverage, SNs are considered with mobility, the ability to form dynamic topologies, and tailored QoS for highly critical local applications, even involving complex orchestration among multiple SNs. Furthermore, SNs can integrate diverse 3GPP and non-3GPP technologies and their capabilities.

To help with consolidation and definition, this paper intends to contribute to the topic from three perspectives: 1.) Defining an architectural approach for SNs, 2.) Description of a set of use cases from different verticals, and 3.) Deriving gaps as input for future standardization activities. This paper is a result of the work on SNs in context of the German research project "6G ANNA" with federal funding from the German Ministry of Education and Research (BMBF) and its funding program for 6G research. The core aim of this project is to develop the key aspects of a holistic, sustainable, secure, and resilient 6G system design that will simplify and improve the interaction between humans, digital assets, and the physical environment.

The remainder of this paper is organized as follows: In Section II, we will approach the idea of SNs from the perspective of well-known 3rd Generation Partnership Project- (3GPP-) network types and respective terminology to generate a common understanding. Further we will classify and characterize the concept of a SN on an abstract level. Section III will then pin-point the challenges associated with the concept in contrast to existing solutions in 5G. Further details on aspects about CN, RAN and application awareness can be found in the respective Sub-sections III-A to -C. In Section IV, we further define our concept with respect to existing architecture paradigms, as well as providing details to key properties like interaction and coordination. To close the loop towards applications, Section V will describe the use of our SN concept in the context of different application scenarios, ranging from Vehicular, Robotics, Airplane and Emergency Services to Remote operation (see Sections V-A to -E). Section VI, then will highlight the area of existing technological concepts and their differences with respect to SNs which can be studied further in the standardization forums necessary to facilitate realization of SNs within future 3GPP standards. We will finally conclude our work and provide an outlook in Section VII.

II. NETWORK TYPES AND CLASSIFICATION

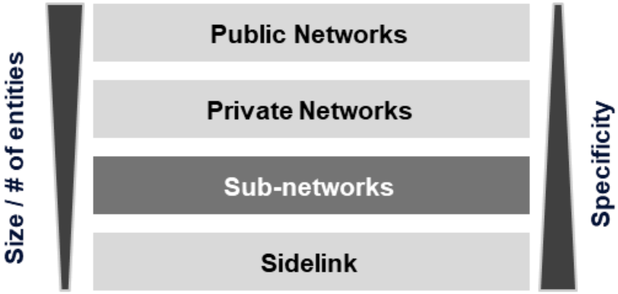

FIGURE 1 5G network types standardized in 3GPP (light gray), arranged by size and specificity to classify the novel concept of Sub-networks within the 3GPP scope.

Throughout the history of 3GPP, various network types have been established in the field, to serve different communication needs. These include Public Networks, which are widely accessible and often cover entire countries, followed by Private Networks (or Non-Public Networks), which are restricted to specific users or organizations. Finally, point-to-point links, known as "Sidelink" in 3GPP to provide direct communication between two devices. These networks can be ranked by size and number of User Equipment (UEs), typically assigned to them, as well as their specificity in terms of design to meet requirements for a specific use case, as shown in Figure 1. This diversity in network types allows, to a certain degree, for tailored communication solutions to be deployed for a range of applications and industries.

We can approach classification of the SN concept based on these existing types to get a clearer understanding of its use and thus requirements in terms of specification and key performance indicators (KPIs). One of the main motivations for SNs is the demand for extreme requirements related to certain applications that need information exchange between UEs, located in a spatially limited area. Typical requirements are extreme quality of service (QoS), i.e. strict latency and high availability. In this context, the term in-X SN then is used to describe such integrated local networks that allow to fulfill these extreme requirements within a "X", standing for a robot, machine, body, or vehicle [15]. Looking towards standardization, there have been some contributions describing similar applications and promoting the concept of SNs, but at the present time there is not yet a common definition or even specification from 3GPP-side as for the well-defined network concepts like "Public-", "Campus-/Private-" Networks or "Sidelink". But, based on the mentioned motivations, we can categorize the concept of SNs somewhere in-between the two existing ones, Private Networks and Sidelink (see Figure 1). For the sake of completeness, it has to be mentioned here, that there exists another related concept, called personal IoT network (PIN) introduced to 3GPP in Release 18. Here the fundamental difference to the SN concept is, that the PIN is focused on secure and localized connectivity for an individual's devices via a gateway, while 6G subnetworks represent a broader

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TABLE I: CLASSIFICATION OF THE SUB-NETWORK CONCEPT RELATIVE TO WELL-KNOWN NETWORK TYPES

	Public Networks	**Private Networks**	**Sub-networks**	**Sidelink**
Typical Dimension	Country/ Regions	Building/ Local Premises	< ~100 meters or use case specific	< ~100 meters
Typical Number of Nodes (UEs)	Millions	Thousands	Hundreds	Two
Spectrum/ License	Country-wide	Local or country-wide	Dynamically sublicensed/ shared license exempt	Country-wide or license exempt
Network Mobility	No	Nomadic	High	High
Autonomy from PN	Inherent	Depending on deployment model	Dynamic/ configurable can be tailored to use case, but more scalable than Sidelink	Mode 1/3: No Mode 2/4: Yes
Survivability without Parent Network	n/a	Depending on deployment model	Temporary for highly critical apps Minutes/hours for general connectivity	High
Use Case Centricity	Low	High	Very High	Very High
Management Interfaces	3GPP	3GPP	3GPP	3GPP
Access	3GPP	3GPP	3GPP, non-3GPP, wireless, wired	3GPP

paradigm shift, offering dynamic and intelligent extensions of the core network, as it will be described later on [16].

In Table I, a list of descriptive characteristics of mobile communication networks has been compiled. This list allows already to get an impression of relevant aspects, that need to be investigated towards adaption of the novel concept. Basically, Core Functions and interfaces are the same for all these network types. Thus, in this paper, following 3GPPs spirit of long-term evolution, we envision 6G SNs to be built based on existing 5G concepts and interfaces, such as the already defined CN functions and their interfaces, as details will show in Section IV. According to the classification shown in Table I, a SN can be defined as a network, that provides use case centric connectivity in an (often, but not exclusively) spatially limited area. In contrast to generic 6G networks, the KPIs of the provided SN connectivity will be more specifically tailored or configured to the associated use case. SNs can be attached to a parent network (PN), e.g. a public network, but may work (at least for some time) even with temporary loss of connection to the PN. A SN has some control over radio resources, can provide local communication and computation, is non-stationary, and may consist of connections provided by 3GPP-based and/or non-3GPP-based technologies. SNs might be nested and need to provide 3GPP-based interfaces to be integrated into an overall 6G infrastructure.

To get to a more precise and technical definition of the term SN, we will continue in three steps: First, we will introduce two characterization schemes, that allow to cluster different implementations of SNs into a) three categories with respect to their Core Network (CN) integration, and b) a definition of different autonomy levels will be provided. Second, we will point out respective challenges in Section III, that need to be addressed to implement SNs according to the provided categories. And third, we will define a technical architecture in more detail in Section IV.

A. Architecture Characterization

To cluster SNs by their characteristics, three “Archetypes” can be defined, based on the “completeness” compared to classic Private- or Public Networks. Due to the fact, that the amount and capabilities of Core Network NFs provided by a SN can widely vary in implementation serving different use cases, it was decided to do the characterization mainly based on the proportion of the internally hosted CN NFs. The Archetypes range from “Fully Integrated Core”, via “Partially Integrated Core” to “Core-less” (summarized in Table II). A “Fully Integrated Core” is a SN archetype, characterized by its adherence to 3GPP standards and CN NFs. It encompasses a complete 3GPP RAN and respective CN. This means that this archetype can be deeply integrated with a PN due to its support of 3GPP standardized interfaces. Additionally, this archetype may also have a high degree of autonomy due to the availability of a complete CN within the SN, i.e., it can carry out all the functions of a 3GPP cellular network. In addition, an intermediate archetype of the “Partially Integrated Core” SNs is defined. This Archetype is characterized by its ability to internally provide 6G RAN connectivity and host at least a partial 3GPP CN locally. But in contrast to the Fully Integrated Core, only a limited degree of autonomy can be reached. For the implemented CN NFs, integration with the PN Core will be deep since both will support 3GPP compliant interfaces. Both, the Fully- and Partially integrated Core Network archetypes, host a 3GPP compliant RAN for their respective clients. For Core-less SNs, finally, dependencies on 3GPP technologies and interfaces are minimal. Those might therefore only expose backhaul connectivity to a PN, e.g. a UE, or an Integrated/Wireless Access and Backhaul (I/WAB) interface. Consequently, such a Core-less SN might operate more as a Gateway and thus may not provide 6G-native CN interfaces to the associated PN.

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TABLE II: SUMMARY OF SUB-NETWORK ARCHETYPES, HELPING TO CLASSIFY DIFFERENT IMPLEMENTATIONS OF SUB-NETWORKS BY PROPERTIES OF INTERNAL AND EXTERNAL INTERFACES

Archetype	SN Properties	
Fully Integrated Core	**RAN:** 3GPP RAN interface towards SN-UEs **Core:** SN includes a dedicated 3GPP CN	**3GPP-Compliance:** All relevant interfaces towards the PN are provided **Interaction:** Full integration of SN into PN[1]
Partially Integrated Core	**RAN:** 3GPP RAN interface towards SN UEs **Core:** SN includes partial 3GPP CN	**3GPP-Compliance:** A subset of 3GPP interfaces or proprietary tailored interfaces to the PN are provided **Interaction:** Selected interfaces for CN elements allowing interaction of SN and PN
Core-less	**RAN:** Independent from 3GPP[1] **Core:** SN does not include any 3GPP CN elements	**3GPP-Compliance:** No 3GPP interfaces other than a regular PN to UE interface w/o additional coordination **Interaction:** Backhaul 3GPP interface towards PN[1]

B. Autonomy

When investigating operation of SNs, it is important to define how SNs can react to a loss of connection to the PN. Communication to the Internet or application servers can become unavailable, but there can be different flavors of locally available services. This ranges from limited operation of the SN to fully independent functionality, depending on the use case's needs. Therefore, we define different levels of autonomy for SNs, as detailed below. There can be SNs which support no, simple, advanced or even full autonomy. The need and feasibility for a specific level of autonomy is defined by the use cases. Examples for use cases and the required level of autonomy can be found in Section V.

L0 - No autonomy:

In this case the SN can be compared to a group of UEs, with potentially some extra functionality for group members. However, in this case a link to the PN is always needed as the local SN traffic (direct or indirect communication) between the UEs is managed/enabled by the PN and becomes unavailable without the PN connection.

L1 - Simple autonomy:

In this case the local connectivity is maintained when the link to the PN is lost, however, other services like adding a new user become unavailable. This means that the SN handles the local SN traffic (direct or indirect communication) on its own while out of coverage. Any additional services become unavailable. The SN just reconnects to the PN after restoration of the coverage.

L2 - Advanced autonomy:

In this case the local connectivity as described in L1 is maintained. On top, other selected services of the PN, such as adding a new user, remain available. This means that the SN handles the additional services on its own while the link to the PN is lost. For these additional services, it is necessary for the SN to synchronize Control Plane (CP) data with the PN while the SN is connected and, in particular, after the connectivity to the PN is restored. While out of coverage, the SN operates this additional functionality in an autonomous way.

L3 - Full autonomy:

In this case, the SN can operate completely independently and in autonomous mode. This means that the SN can be compared to a fully operational 6G network within the 6G network, including a full Core Network (CN). As described in L2, the state of affected CN components needs to be synchronized with the PN, while in coverage of the PN. While the SN is connected to the PN, additional services can also be available.

Lastly, the degree of autonomy the UEs and SN possess will greatly influence what they require from the network. Highly autonomous devices that can operate independently are expected to be less dependent on infrastructure-based networks for performing their functions. To implement these different levels of autonomy, the set and extent of Network Functions (NFs) to be implemented within the SN can be tailored. A more detailed overview of the internal perspective of a SN will be provided in the following Section.

III. SUB-NETWORK FUNCTIONALITY AND CHALLENGES

Building-up on the external perspective on SNs in the previous chapter, the following sections of this chapter will describe the perspectives of SN functionalities.

The first Paragraph contains remarks about basic SN functionalities and is structured in five items which discuss general functions, application functions, and specific functions of layers 1, 2 and 3. The following sections focus on challenges for Core Network Functions (Paragraph B), Radio Resource Management (Paragraph C), and Application Awareness (Paragraph D)

A. Functional Challenges

Functionalities across the entire International Organization for Standardization- (OSI-) reference model, will need to provide certain functionalities for future SNs. These functions can be realized either in an ad hoc manner without relying on centralized infrastructure, or in a managed style by centralized entities such as Base Stations (BS), Controllers and Core(s). Examples might be centralized radio resource management (RRM) vs. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) on physical layer, or static point-to-point routing between UE and Next-Generation Node B (gNB) vs. dynamic packet routing on link layer.

In the following, most relevant aspects and associated challenges will be briefly introduced. Starting with general Sub-network functionalities and Application functionalities that are of generic nature, followed by challenges categorized by OSI layers, for those that can clearly associated to one layer. The list is not meant to be exhaustive but intends to give an overview of most relevant aspects.

1) General Sub-network functionalities:

Self-Configuration: Each node in the network should be able to automatically adjust its settings and parameters based on the current network conditions. This includes identifying available neighbors, establishing connections and setting optimal transmission power levels. This feature is critical, especially when the network topology can change frequently, e.g., due to mobility of the nodes.

Scalability: As the number of nodes in the network varies, the network should continue to operate efficiently. Scalability issues can include maintaining routing efficiency, managing increased network traffic, and minimizing interference between nodes. There is likely to be a trade-off between complexity, performance and scalability that should be made based on the specific SN purpose and deployment requirements. Note that while a larger number of devices, in the first place creates challenges (for Layers 1, 2, and 3), once they are solved, it becomes a characteristic that provides value to the SN (e.g. by reliability of local communication).

Robustness: Nodes in a SN can fail, lose connectivity or leave the network at any time, and new nodes can join. It is desirable for the network to be able to handle such changes without significant disruptions.

QoS: The SN should have mechanisms to allocate different priority to specific nodes, applications, or data flows, or to guarantee a certain level of performance. This can include parameters like bandwidth, latency, jitter, and packet loss.

Network Security, Authentication and Authorization: Unauthorized access or data leakage should be prevented in a SN. The identity of a device or node should be validated before it is granted access to the SN (authentication). Subsequently, the level of access or the specific resources with which the authenticated device or node may interact should be determined (authorization).

SN and PN Mobility: Need for concepts to deal with mobile network elements results from mobile SNs, or mobile components of the PN like Non-Terrestrial Network- (NTN-) components such as satellites, which may carry RAN elements. Also, parts of the 6G network being deployed in trains, cars, airplanes, and ships transform parts of a 6G network into dynamic elements that have been static until today.

2) Application functionalities

Time Synchronization: In many cases, nodes in a SN need to agree on a common time reference. This is crucial for coordinating actions and time-stamping data or events. Factors that make it challenging include clock drifts, network latency, and potentially the lack of a central time server in a SN. The existing Precision Time Protocol (PTP) profiles for cellular networks should be a starting point for evaluations [17].

Ranging:

Localization and ranging capabilities play a critical role in communication procedures and boosting network efficiency. They allow for localized communication by enabling nodes to determine their positions, which helps in reducing unnecessary traffic. This ability is particularly beneficial in node discovery, a crucial function in ad hoc networks due to the constant change in node positions. By knowing the positions of other nodes, a node can schedule transmissions in a way to avoid interference, thereby reducing the chances of packet collisions and improving overall network performance. Furthermore, the information gathered from ranging helps in routing optimization by determining the optimal data transmission path, enhancing efficiency and speed of data delivery. In context of SNs, additionally collaborative ranging, leveraging proximity of multiple SNs is an aspect that needs investigation, as well as the use of SN- and SN-UE position for the purpose of interference-management and mitigation.

3) Layer 1 functionalities:

Synchronization: Alignment of signals in time, frequency, and space is an important element for coordinating (concurrent) channel access to be considered for inter-SN, as well as SN-PN interaction. It is more challenging in ad hoc type of topologies and when QoS guarantees are to be provided.

Adaptive Power Control: In dynamic environments, the optimal transmission power level can change over time due to factors like node mobility, changes in channel conditions, and variations in network traffic. Algorithms to adjust the power level either in response to these changes, or predictively, will facilitate dynamic spectrum re-use among SNs and potentially unlock more advanced frequency planning methods.

4) Layer 2 functionalities:

Resource Allocation and Reservation: Allocating time slots and bandwidth requires balancing different priorities, such as maximizing overall network throughput, ensuring fairness between nodes, or prioritizing certain types of traffic. In addition, for certain types of traffic, it may be necessary to reserve resources in advance to ensure a certain level of QoS.

Neighbor Detection: In an ad hoc type of SN, each node in the network needs to discover and keep track of other nodes within its direct communication range. Also, an estimation of the quality of corresponding links would likely be beneficial.

Sleep-Wake Synchronization: To save energy, nodes could periodically switch between active and sleep states. Synchronization of these sleep-wake cycles can ensure that a node does not attempt to communicate while its neighbors are asleep, and vice versa.

Error Checking and Control: To ensure the integrity and reliability of data transmission mechanisms for

- error detection, which checks if data has been altered during transmission,

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- forward error correction (FEC), which allows the receiver to detect errors without the need of a re-transmission,
- automatic repeat requests (ARQ), which ensures corrupted packets are retransmitted, and
- hybrid ARQ (HARQ), which combines FEC and ARQ should be present.

5) Layer 3 functionalities

Routing: It is essential to be able to identify and maintain the best path between two nodes or devices, especially in SNs with low node density, SNs spanning large areas, or networks of SNs. Different approaches with latency, overhead, and robustness trade-offs can be considered.

Generally, the listed functionalities can be realized through centralized coordination, in a decentralized manner, or a hybrid approach between the two. The choice can vary for each individual functionality case-by-case, depending on application purpose and deployment needs. In addition, careful trade-off between device complexity (cost), resource efficiency (CP overhead), application needs (QoS), and device autonomy needs to be made. This gives an impression for the need of investigation together with use cases, more specific requirements, and a more detailed concept for a SN-enabled 6G architecture.

B. Core Network

The 5G CN represents the heart of the fifth-generation mobile network technology, designed to meet the ever-increasing demands or high-speed data, low latency, and massive device connectivity. Unlike its predecessors, the 5G core network introduces a service-based architecture (SBA) that enhances flexibility and scalability. Central to this architecture are various NFs, which are modular software elements that handle specific tasks within the network. These NFs communicate with each other through standardized, web-based protocols and defined Application Programming Interfaces (APIs), referred to as Service Based Interfaces in 5G (SBI). Each NF exposes its capabilities as services that can be discovered and invoked by other NFs, fostering a dynamic and scalable environment. 5G core NFs, such as Access- and Mobility Management Function (AMF), Session Management Function (SMF), User Plane Function (UPF), etc., work in concert to ensure efficient and seamless communication. By decoupling hardware from software and leveraging cloud-native technologies, the 5G CN provides high performance and the agility to support a wide range of applications, from autonomous vehicles to smart cities and beyond. Thus, towards 6G and 6G SNs, it appears to be a logical approach to take the 5G CN, and its architecture as a baseline to identify potential modifications and extensions needed to address the mentioned challenges.

From the SN point of view, the CN needs to support flexible interconnection between SNs and/or a PN. SNs may be connected to a PN and/or other SNs in a variety of topologies which may include hierarchical, flat, as well as hybrid topologies (see Paragraph D for more details).

An additional layer of complexity is added by varying SN capabilities. This can be characterized by different autonomy levels during its operation as mentioned in Section II-B. This means that it could include complete, partial, no CN, or dynamic CN capability during its operation. A complete CN capability indicates that the SN hosts a complete CN that can provide an independent control and data plane for all its connected UEs. A partial CN capability could result from hosting a subset of CN capabilities. As an example, the SN may only host data plane related NFs e.g. session management and data routing functions like the 5G core networks SMF and UPF components. For the partial CN capability, the SN needs an interconnection with the external network (PN or another SN). A mechanism to offload the core network responsibilities from the SN to PN is also needed. In the case of dynamic networks, the SN with partial core network capability needs to signal reduced capability to its UEs in case of connectivity loss to PN. Finally, the SN may be resource constrained and unable to host a CN. In this case, it will completely depend on a PN for CN capabilities. In case of connection loss towards the PN, it will need to gracefully shut down its services offered to its connected UEs. The SN may also have a dynamic capability. This means that it may adapt its capability to the availability of CN capability in a PN. In case of acceptable connectivity with a PN, it may offload core network capabilities to reduce energy consumption. Once there is a connectivity loss, the SN may gracefully handover the responsibility to its local core network.

Hence, the 6G SN concept requires that the CN supports the dynamic interplay between SNs and PNs. Additionally, the network core functions should support roles that are dependent on their capability. These roles may be primary, secondary/proxy, fallback, transparent relay, unified, or mesh network function. A full CN capability would indicate that all the core NFs can operate in a primary role i.e. they can autonomously serve the requirements of the SN UEs. In a partial core network capability, the core NFs would operate in a secondary or relay mode. This means that the core NFs of the SN would always depend on the parent-NFs. They could either act as a transparent relay between the SN UEs and the parent core NF or the SNs core NF could act as a proxy for the parent core NF. In case of dynamic CN capability, the SN core functions may be in a fallback role to provide services in the case connectivity with PN core functions is lost, or in a unified role where the core NFs are synchronized across the PN and SN. Similarly, a mesh role for core NFs would enable mesh connectivity between them and promote self-healing by flexibly reconfiguring the NF roles suited to the current mesh topology.

C. RRM Within and Among Sub-Networks

In addition to hosting a CN, the 6G SNs must provide a Radio Access Network (RAN) to connect UEs to the SN. Such a

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RAN may consist of 3GPP standardized RAN like 4G-, 5G- or future 6G RAN. The UE may employ Sidelink as well as Sidelink relay communication modes to connect to the SN or between UEs. The SN may also consist of a non-3GPP access like Wireless LAN (WLAN), Long Range Wide Area Network (LoRaWAN), Bluetooth, low-rate wireless personal area networks (LR-WPAN, e.g. IEEE 802.15.4) or some other wireless technology to provide SN connectivity.

For 3GPP standardized RAN, the data and CP will be provided by the CN and RAN directly. In the case of non-3GPP RAN, the data and CP will be provided by the CN via an Interworking Function (IWF). The IWF enables the integration of non-3GPP radio access features with 3GPP core network components. It could be flexibly placed in either the PN or SN.

Integration within a 6G network

The concept of SNs demands intensive interaction between the PN and the SNs. Essential RAN functions, such as RRM, should be carefully adjusted to the SN concept and should be characterized by a certain “freedom” in choosing the radio resources on a SN level. The reason for this is because the PN is not able to have a continuous and detailed overview of the channel conditions and dynamic environmental changes in each SN. Thus, it lacks the information quality to decide for optimal distribution of radio resources on small time scale, especially if we consider strict latency and reliability requirements. This is essential, among others, in areas of motion control, factory automation, robotics, and flexible manufacturing.

The SN should be given a certain level of autonomy while allocating both, time- and frequency resources, or even doing further RAN configurations to enable coexistence with other SNs without jeopardizing any QoS requirements. This will allow to utilize the resources in a more efficient way, since they will be reused when they are needed. To avoid continuous looping between a set of resources among two or several SNs, further consensus reaching mechanisms should take place between the SNs. These might be driven by the SN-controllers and deployed using direct connections between them, as illustrated in Figure 4.

According to the SN definition, the SN is formed based on local communication needs, the SN is aware of the dynamic changes in its environment and proximity in a more detailed and up-to-date manner than the PN. Hence, the SN, using techniques such as sensor data fusion, interference management and spectrum sensing, is able to decide the temporal and spectral usage of resources, without necessarily asking for permission from the PN. The SN should have the autonomy to choose its own resources, to some extent also independently of the PN.

Hence, mechanisms to realize long-term RRM (e.g. bulk communication resources from PN to SN) and short-term RRM, such autonomous RRM on SN level should be introduced in the future standards of 6G communication.

D. Application Awareness

With the increasing dynamicity of the network architecture and the strong increase in deployment variety in the upcoming 6G networks, it is important to increase network-state- and topology-awareness of the application layers.

In the future it will be necessary for applications to react to dynamic network topology changes automatically, since manual intervention will not be possible anymore due to the dynamic nature of network topology. Network quality is improved by only generating the amount of traffic that the network can support. Applications optimize the overall network cost for their data flows when they are aware of the underlying network and its topology. If the applications are topology- and network-condition aware, the application functionality can be retained even if the SN is disconnected from the PN. In this scenario, the SN operates in temporary autonomous mode and compute resources used by the application are available in the autonomous SN.

The use of network digital twins can make applications aware of future changes of the topology and thus enable them to prepare for such changes beforehand – limiting the impact of their users’ quality of experience or bringing machines into safe states in industrial use cases.

The application layer is made aware of network conditions through interfaces to the network. Standards, addressing this are the ETSI Multi-access Edge Computing (ETSI-MEC) activity [20] and the Linux Foundation CAMARA API [21]. They define control-plane-like interfaces, e.g. to discover resources, model the locations of UEs and/or inform applications about the current network status. The interfaces are modeled through REST calls [22] [23].

Other technologies, driven by Internet Engineering Taskforce (IETF), can also make applications aware of the current congestion situation and are user-plane-like interfaces. Low Latency, Low Loss and Scalable Throughput (L4S), for example, tags data packets with information that lets the application infer the congestion status at the packet level [25]. The previously mentioned technologies, however, do not model potential dynamic SN topology changes. Further, there is a lack of capability to convey predictive information and a holistic view of the network. This gap needs to be addressed which can be done by modeling SN in a coarse-grained way towards the application.

Sub-networks as Seen from Application Domain

To allow an application to use knowledge about SNs, we can abstract SNs to a simple model: A SN for the application is a part of the overall 6G network that is connected through a link to the parent network. In the following sections we use the term topology to describe sets of SNs along with their links to the parent network (including information about basic technical and application relevant KPIs). Future work may consider a more refined version of the aforementioned abstraction which models SNs containing other SNs (nested SNs are not covered here).

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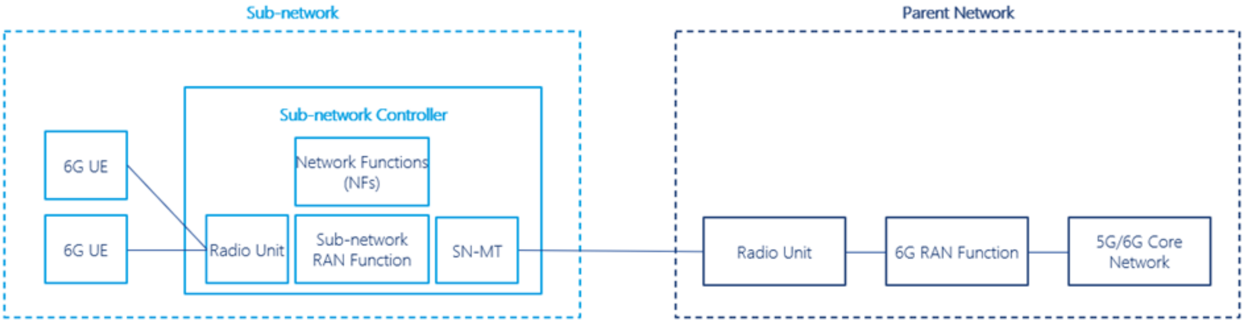

FIGURE 2 Top-level architecture of a Sub-network, showing its connection to the Parent Network side (PN), as well as the Sub-network itself, it's main components (building the Sub-network Controller, SNC) and associated 6G UEs.

Based on the ETSI-MEC, here a zone is defined as a set base stations and geolocations [24], SNs can be modeled in a similar way with following additional information:

- The characteristics of the backhaul link(s) connecting the SN to the broader 6G infrastructure, including the link to the PN and parameters like estimated maximum bandwidth, latency, and reliability. These characteristics are essential in determining the SN's data transfer capabilities to other SNs.
- Information about compute resources that can be used by application layer.
- The movement of the SN and its effect on the application[1].
- Capabilities of the SN in a potential temporary autonomous operation. This capability describes the functionality needed by the application when the SN operates in an autonomous mode.
- The granularity of SN modeling towards the application domain must be determined by the PN – it should be an abstracted version of the complete knowledge that network has.

Applications may also be implemented as a collection of services which are flexibly deployed in both SN and PN. Providing services to SN UEs becomes challenging when the topology changes. To cater for seamless service provisioning in a dynamic topology, services need adaptation mechanisms in response to network condition and topology information. Such adaptation mechanisms could include a service joining mechanism when new SNs join the existing topology and a service splitting mechanism, required when SNs are disconnected from PN or neighbor SNs. Such a service joining mechanism could be implemented in multiple ways, according to the unique service requirements. These could include electing a primary service provider, electing a service fallback provider, parallel operation with unified service state, setting up a service as a relay etc. The exact nature of service joining, and service splitting depends on the unique characteristics required by the service. Consequently, service splitting would require synchronizing to the latest service state and a graceful switch from dependent operation to autonomous operation. The following list classifies different topology types and summarizes how services like authentication, content distribution and QoS provisioning could be impacted by changes in the network topology, with examples:

Hierarchical Topology (Fully-, partially dependent service provisioning) – Examples:

- Authentication service may be provided by parent- or neighbor SN only. The SN may act as a relay for authentication service related signaling to its subordinate SNs or hosts.
- Content distribution service in the SN would treat the connected network as content source. The SN service may act as a content cache to its hosts or subordinate SNs.
- QoS provisioning service would require connected networks to guarantee QoS specific resources.

Flat Topology (Partially dependent, independent service provisioning) – Examples:

- Authentication service may be provided independently by either parent- or neighbor SNs or the SN itself. A unified authentication service may also be feasible in this topology.
- Content distribution service may be provided by SN or neighbor SNs. The SN may act like a content cache, or it might distribute the content independently to its hosts.
- QoS provisioning service would be provided by the SNs on best effort basis. A distributed mechanism would be required to guarantee QoS satisfying resource assignment between the PN or neighbor SNs and the SN.

Hybrid Topology (Completely dependent, partially dependent, independent service provisioning) – Examples:

- Authentication services may form a federation in this topology. In this manner, authentication may be

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[1] The movement of SNs, particularly in mobile environments, can significantly affect the application layer in several ways. SNs typically consist of a SNC and a group of SN devices connected to it, and when this entire structure moves, it introduces dynamic changes that impact network performance, which in turn can affect application behavior. The application-side might be affected by the following parameters impacted by SN movement: Increased latency, packet loss and degradation of QoS, handover interruptions, throughput, jitter and unstable latency, signal strength variability, etc.

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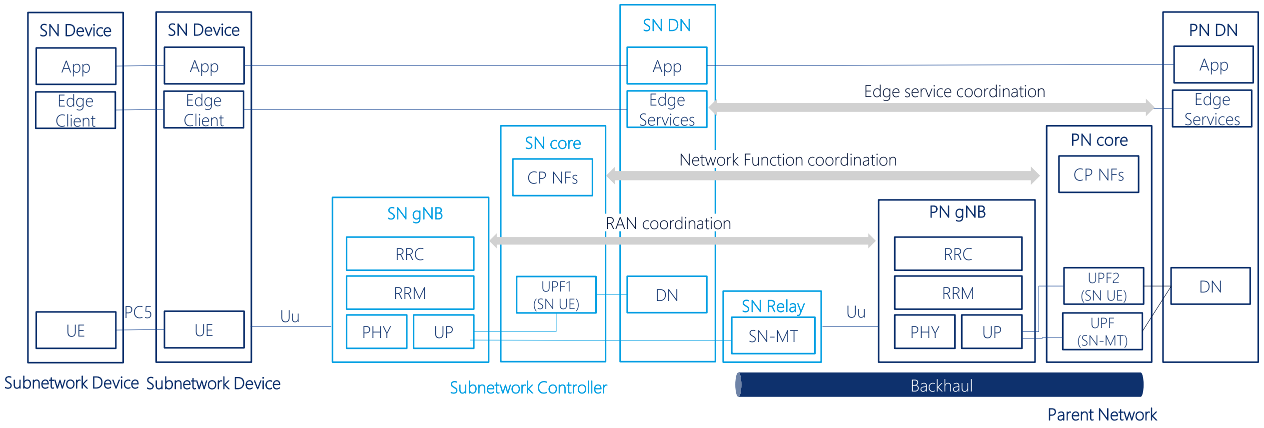

FIGURE 3 More detailed visualization of involved components, including Network Functions on different layers. Visualized with grey arrows: The Sub-network coordinates on various layers including RAN, core, and services such as edge computing as L3 relay solution.

provided by both SNs and parent- or neighbor SNs. Connected PNs or neighbor SNs may dynamically join the federation or leave it.

- Content distribution services may be delivered as a combination of content sources and caches.
- QoS Provisioning service might be performed jointly or distributed depending on the current topology.

IV. SUB-NETWORK ARCHITECTURE

To come a step closer towards implementation, coming from rather abstract classification in Section II and a more functional perspective on SNs in Section III, we can now focus on the implications on architecture of SN. The envisioned architecture of a SN is shown in Figure 2, comprising the Sub-network controller (SNC) and SN devices indicated by the “6G UEs”. A key role is taken by the SNC, which manages the devices in the local SN. The capability of the SNC is dependent on the supported autonomy level. It may range from a high capability SNC which includes a full CN and edge services for autonomous operation to a low capability SNC without a core network or edge services, which is dependent on PN.

The SN is connected via the SNC to the PN through a backhaul connection. There are various ways in which SNs can connect to the PN. It depends on the capabilities of the SN as well as network design principles for a specific use case. In principle, SNs can communicate with each other horizontally and vertically. We are focusing on the hierarchical, one-to-one connection of SNC to PN in this paper. Other architectural designs as well as implementation aspects and spectrum are out of focus of this study. The Sub-network mobile terminal (SN-MT) terminates the Uu interface to the PN using procedures and behaviors as specified for a UE. The PN can be a public operator network or private campus network. Over this backhaul link, different management and control functionalities are implemented using interfaces between the respective networks, enabling the SN with additional features it cannot offer on its own.

At the RAN level, the SNC can expose an interface to the RAN of the PN, which can be used to enable centralized RRM (see RAN Coordination interface in Figure 3). To manage a high density of SNs, especially in a mobility scenario such as the in-vehicle or the cooperative, carrying autonomous mobile robots use case (explained in detail in Paragraphs V-A and V-B), a RAN coordination becomes beneficial to avoid interference between SNs and achieve a higher frequency reuse. In the CN, an interaction or sharing of network functions (NFs) between the SNC and the PN can be achieved. At the edge service layer in the data network, the PN edge Service and the SN edge Services can be coordinated by e.g., topology-awareness of the SN, allowing dynamic offloading of services between SNs and PN infrastructure. Such edge service layer will be responsible, for example, for managing tasks among the Sub-networks, checking the state of the SN devices (e.g. functionalities and capabilities of the nodes, battery lifetime, managing which SN device belongs to which SN, etc.)

The proposed architecture to enable the described SN features is an extended relay solution which is based on a backhaul architecture with local breakout and is visualized in Figure 3.

In the proposed architecture, inspired by the Wireless Access Backhaul (WAB) [18], a Layer 3 relay solution is integrated. It enables intra-SN communication, i.e., SN-UE to SN-UE and SN-UE to SN-edge service via a local Data Network (DN). Furthermore, the backhaul connection enables SN to PN communication for the user plane (UP) related procedures, i.e., offloading to PN edge service, as well as potential CP related coordination between PN and SN (RAN and core network system services). The SNC provides gateway functionality and enables wireless backhauling via SN-MT, provides radio access to the SN-UEs with a SN gNB (Sub-network gNB), and allows for local communication by providing a User Plane Function (UPF) for SN-UP termination.

As it can be seen from PN-UPF for SN-MT in Figure 3, the backhaul connection is realized by utilizing a 6G relay UE and a dedicated UPF. It carries the coordination messages between SN and PN as well as the UP data.

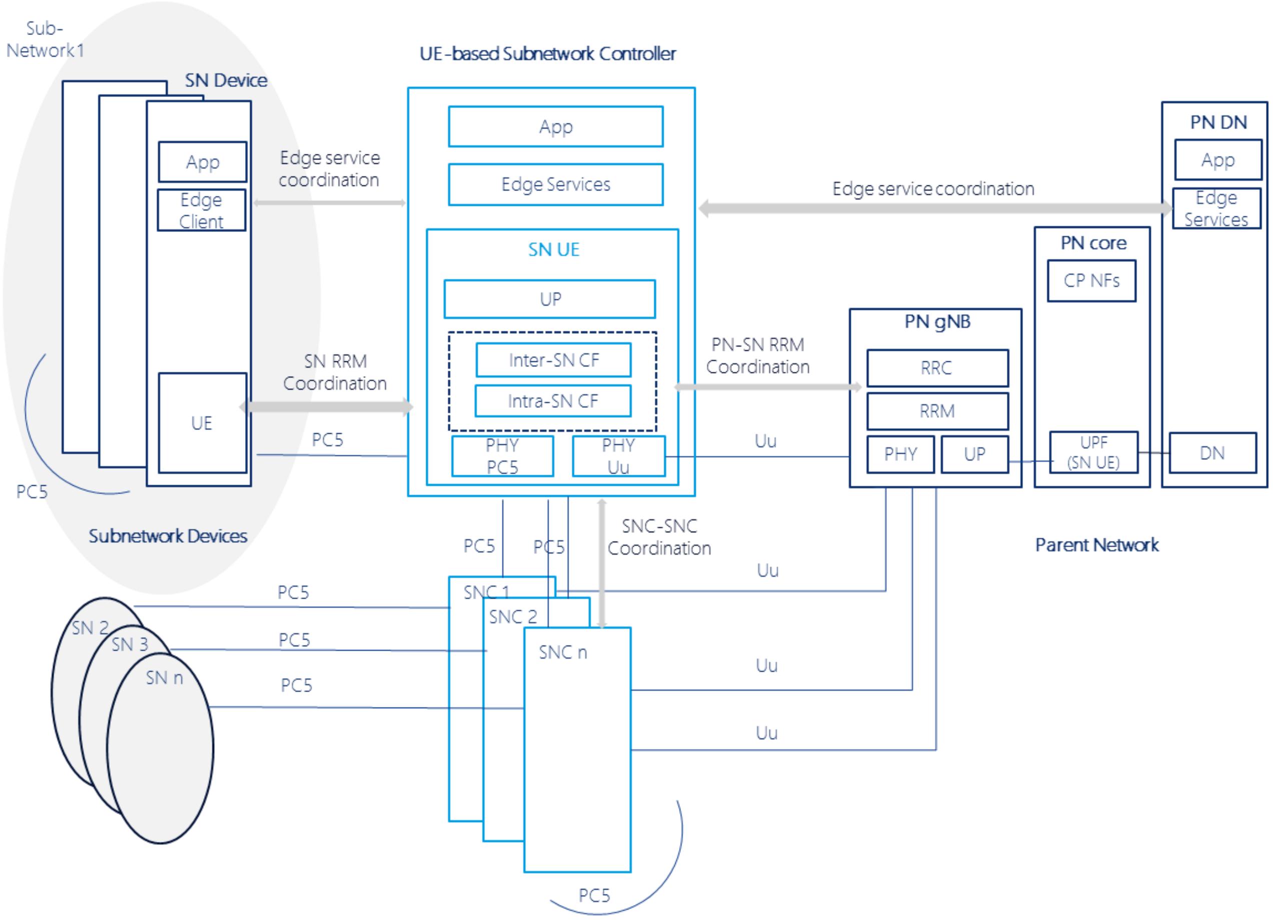

FIGURE 4 An extension to the proposed SN architecture, where the SN controller runs on a SN end device and D2D communication is enabled within a SN.

For intra-SN communication, i.e. local breakout, the traffic of the SN-UE is terminated at the UPF located in the SN. 5G standards already support flexible deployment of the UPF in various locations within the network. Local communication and local computing relieve the burden on backhaul connection and reduce the latency meeting use case requirements with enhancing the privacy and security matters. For communication towards the PN, traffic of the SN-UE is terminated at a secondary PN-UPF (see PN-UPF2 for SN UE in Figure 3) using the backhaul link between 6G SN Relay UE and PN gNB.

To realize both, the intra-SN communication, and the communication towards the PN, the SNC can perform Internet Protocol (IP) routing, i.e., Layer 3 relaying. Internal traffic is routed towards the intended destination at the SN-UPF local breakout point and traffic towards the PN is routed towards the SN Relay to be relayed to PN.

This architecture does not require standardization changes to the UE and RAN protocol stack as it uses existing 5G options. This limits the complexity and implementation effort but challenges the coordination between SN and PN for e.g., intra-RAN synchronization. From UP perspective the SN operation is stand alone and fully autonomous. For CP procedures, the SN's autonomy level determines if PN connectivity is needed. Thus, in case of unavailability of the PN, the operation of the SN can be limited or terminated. If a higher level of autonomy is desired in the SN, further CP functions (e.g., AMF, SMF, Policy Control Function (PCF), Unified Data Management (UDM)) could be added in the SN to handle SN-UEs without the need of reaching the PN. These CP functions could have limited scope, e.g., handling only a use case-specific subset of SN-UEs for which communication should be highly reliable and hence possible also when PN is unreachable.

At the service level, the coordination of any distributed service framework such as edge computing can be achieved. This would allow dynamic function offloading between the SN and compute resources available in the PN. An important aspect in that regard is the topology-awareness of the SN for the application, as introduced in Paragraph III-D. The details of network management procedures like primary authentication and handover are use-case specific and require additional investigation on the details for implementation.

In use cases where latency and reliability demands are very strict and in which the SN-UEs are grouped in such way, so that they perform a common task, the role of the SNC can be taken over by a SN-device or a UE (see Figure 4). This enables faster reaction to dynamic changes of the environment by

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introducing various mechanisms for enforcing reliability and latency fulfillment on SN level. Examples for use cases that would benefit of the proposed architecture are the cooperating carrying autonomous mobile robots, V2X communication, flexible modular production, in the domain of industrial manufacturing, and cooperative robotics. Here, one of the SN-devices is designated as SNC and is responsible for the communication with the PN. The PN allocates an initial set of resources to the SN for intra-SN communication, via communication with the SNC. However, afterwards, the SN retains its autonomy and can autonomously change this initial set of communication resources in case, it detects that other communication resources are more appropriate to fulfill the QoS of the application running in the SN. This detection could be done by means of collecting its own local sensing and environmental information, location and perception data. Hence, the main role of the SNC is the local RRM within the SN, designated as "Intra-SN coordination function (CF)" in Figure 4. Further, the SNCs of different SNs exchange information about their environment, communication patterns, used resources and application requirements, as well as coordinate the applications and services that run in them. This functionality is covered in the "Inter-SN CF" block inside the SNC in Figure 4. Therefore, both the SN-devices as well as the SNCs, can communicate via a Device to Device (D2D) communication, e.g. sidelink. Other RAN and edge service coordination between the SNs and the PN can take place between the PN gNB and the SNCs.

V. USE CASES

The following section will cover a range of use cases from different vertical application domains, to give the reader a better feeling of potential implementations of SNs. Each of the use cases will be described in terms of its specific needs and, as far as possible by the authors, enriched by detailed numerical Key Performance Indicators (KPIs). It needs to be mentioned, that this paper is focused on presenting a foundational architectural concept for SNs and mapping them to various use cases. A detailed derivation and in-depth analysis of KPIs, including the performance impact of specific interfaces across different protocols and deployment scenarios, falls outside the scope of this conceptual paper and is left for future investigations.

A. *Vehicular Sub-networks*

Use case description

Use of SNs in context of mobility has been discussed excessively from a conceptual perspective. It can be summarized, that local connectivity with extreme requirements will be an enabler for these applications [4]. These requirements are shared with those of other applications, such as "life-critical systems", "robotics" and "medical appliances", also called "in-body" SNs [1]. Going into more detail, for vehicular communications, we can separate applications into two classes: 1.) inter-vehicle communications (or V2V-/V2X-communication), as well as 2.) in-vehicle communication. The first can be seen as an extension of state-of-the-art inter-vehicle communication, e.g. by 5G Sidelink, so that we use these existing technologies as a baseline for extension of requirements towards SNs. For the latter class of applications, in the field of classic (in-)vehicular communication, there exist communication technologies that have a rich and extensive legacy, that can be investigated to derive requirements towards 6G SNs, thus we will keep a focus on those throughout the following paragraph.

In-vehicle communication architectures, often called electrical/electronic architectures (E/E-A) are composed nowadays a heterogeneous number of different technologies, all designed for a certain set of applications. These technologies are then used to build a static, engineered network interconnecting all Sensors, Actuators, and Electronic Control Units (ECUs) within the vehicle that is referred to as the so-called Vehicle Electrical/Electronic- (E/E)-Architecture.

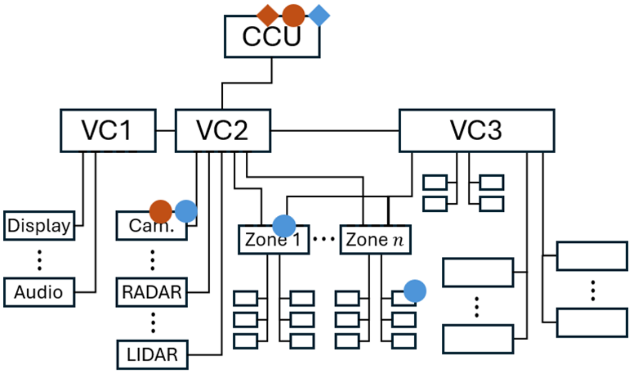

FIGURE 5 **Exemplary block diagram of centralized in-vehicle network. Big rectangles: Vehicle Computers (VC) or Connectivity Unit (CCU). Medium sized: Sensors and Zone controllers, as data sources and data aggregators. Small boxes: low level sensors/actuators [6]. Markers indicate potential nodes of in-vehicle SN (blue) or inter-vehicle/infrastructure SN (red). Circles indicate function as SN-UEs, diamonds function as a SNC.**

Figure 5 shows such an architecture. It comprises technologies with respective KPIs in terms of their communication capabilities, which will be briefly summarized: Bus-technologies like Controller Area Network (CAN-bus), Local Interconnect Network (LIN), FlexRay, and 10 Mb/s Automotive Ethernet (10BASE-T1S) are used, providing communication with real-time determinism and rates below 10 Mb/s [7] [8] [9]. These technologies are used to connect low-rate endpoints to the network, or as a redundant connection with a special purpose (e.g. safety or power management) for nodes, connected with a high-speed interface in parallel. On the compute layer, main technologies are high-speed interfaces like Automotive Ethernet with speed-grades ranging from 100 Mb/s (100BASE-T1) up to 10 Gb/s (10GBASE-T1), mainly for inter-connectivity in between compute- and zonal-ECUs, building-up the so-called backbone of the network [10] [11]. Additionally, for point-to-point applications like RADARs and Displays, so-called "SerDes-" (Serializer/Deserializer-) links with rates in up to

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10 Gb/s or even beyond (forward channel), lower rates on the control channel and no networking capabilities (routing, switching, etc.) come to application.

Inflexibility of these architectures (once fabricated, there are hardly any means to make changes to the wiring harness), rather high production costs (especially for high-speed interfaces) and added resiliency by wireless redundancy are arguments to integrate nodes by 6G SNs into the E/E-A. Further, based on the fact, that every car is equipped with a cellular modem in its Central Connectivity Unit (CCU) already today, it can be expected that at least this node will be 6G-capable in any future E/E-A. This will ease adding further nodes wirelessly from a cost and complexity perspective.

Sub-network description

Thinking about adoption of 6G SNs in this domain, we can identify potential applications throughout the architecture. When focusing on in-vehicle SNs first, as indicated by Figure 5 with blue markers, central SNC (see blue diamond) might be deployed within the CCU, historically acting as a gateway towards outside of the vehicle. But alternative options exist for implementation of the SNC functionality, which might give advantages in terms of redundancy or physical placement. Especially zonal ECUs might host SNCs, since those are acting as a sort of multi-technology hubs, aggregating, translating, and forwarding messages coming in and out via different sorts of physical layer technologies. Also, distributed implementations could be envisioned, where 6G SN core applications might run on one of the Vehicle Computers, while the RAN part of the SNC might be implemented either within the CCU or Zonal ECUs. End-nodes (see Figure 5, blue circles) then might be sensors and actuators that can profit from the advantages of local wireless connectivity, helping to leverage synergies. Today, systems like tire pressure monitoring systems, battery cell monitoring or keyless vehicle access are implemented with separated, independent wireless infrastructure and respective ECUs, and even different wireless technologies existing in parallel. Convergence towards local connectivity with 6G SNs would help to share hardware between the systems and allow for easier integration, thus provide advantages compared to today’s designs. Another key aspect, especially for in-vehicle communication is the required level of autonomy. Here it is essential, that basic communication can be maintained, even if no coverage of a PN is available.

Focusing on inter-vehicle SNs, or vehicle-to-infrastructure SNs (see Figure 5, red markers), potential points for implementation of the controller part are within the CCU, since this part of the E/E-A is exposed to the outside anyways and thus could be integrated into the overall security concept easily. Regarding the SN UEs (red circles), its applications might be reduced to the CCU, acting as a gateway for forwarding or receiving collaboration-relevant messages to external SN nodes and specific sensor types that provide highest gains e.g. for collaborative perception, when shared with others, like Cameras, RADARs or Inertial Measurement Units (IMUs).

Requirements and KPIs

As mentioned in the previous paragraphs, a large variety of application specific technologies for automotive communication do already exist. This allows to derive respective comparable requirements like rate, latency, distance, and startup-time, easily by comparison with respective technologies. Respect to required rates, we can summarize from approx. 20 kbit/s (e.g. bush-buttons) up to 15 Gb/s (e.g. uncompressed camera data) covers the entire range. Excluding rare applications with extreme rates like cameras, a maximum rate of 1 Gb/s would allow to cover a large variety of applications. Regarding latency, values < 1 ms range are required (point to point). To cover application areas within a vehicle, service volumes of $5 \times 5 \times 2$ m for in-vehicle and $0.5 \times 0.5 \times 0.1$ km for inter-vehicle communication should be sufficient. Since startup-time is a critical value as well in both types of application (at startup of a vehicle, all internal communication needs to be established before the driver wants to interact), but even more critically, in dynamic scenarios e.g. at crossroads, when vehicles need to share in formation in ad hoc SNs. Thus, startup should be possible within < 100 ms. This and some additional KPIs are summarized in Table III.

TABLE III:
PERFORMANCE REQUIREMENTS FOR VEHICULAR COMMUNICATION

KPI	Value	Comment
Latency	< 1 ms	
Data-rate (UE)	< 1 Gbit/s	(< 15 Gbit/s in extreme applications)
Communication-Service Reliability	~ 10 Years	Mean time between failures, equiv. ≤ 10 FIT (Failures in Time) for safety relevant features
Message size	1-1500 bytes	
Speed in-vehicle/inter-vehicle	0 km/h/ 500 km/h	Relative vehicle speed, assuming 250 km/h, each
No. UEs, in-vehicle/inter-vehicle	2-100/ 2-50	
Service volume in-vehicle/inter-vehicle	10 ×10 ×5 m/ 0.5×0.5×0.2 km	
Sub-Network startup-time	< 100 ms	Power-on to first communication

Service Flow

For the scenario of in-vehicle, the network operates in a quasi-static configuration: The required nodes are, once assembled to the vehicle during production time, associated with the same SNC and communicate with a pre-configured traffic pattern, that might be optimized for specific vehicle configurations and/or driving situations. Power-cycling of the vehicle itself, needs to be considered, since startup-time is a KPI. Regarding associated nodes or network topologies, there are no dynamic changes to be expected. Thus, the focus here, lies on availability and reliability.

For inter-vehicle use cases, the dynamics can be higher. Here, depending on traffic situations and capabilities of different

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vehicles need 1.) detect proximity to each other 2.) exchange information about goals and capabilities, and 3.) to form SNs. Here vehicles might act either as SNC or SN-UE (see architecture example in Figure 4). This coordination could be assisted by the PN, or in case of no coverage also negotiated between the vehicles autonomously. Once formed, there will be messages and data exchanged to resolve the situation, before the SN will dissolve again.

B. Collaborative and Autonomous Robots in Factory

Use case description

To successfully transition from traditional production facilities to data-driven and autonomous Cyber-Physical Production Systems (CPPS), it is essential to seamlessly integrate components. Previously, connecting these parts was achieved using wired solutions. However, the conversion to autonomous CPPS now relies on all production process components being wirelessly connected. In factories, wireless data transmission between different production areas allows for more flexible system design and faster integration of new components. This enables producers to quickly adapt to changing market demands and dynamic production needs.

The 5G standards have brought new features to radio networks, including private networks. These private networks offer enhanced security, reliability, and control, making them suitable for industrial applications. This progress has made 5G technology accessible to businesses, with national regulatory authorities defining specific frequency ranges for private networks. SNs for 6G in industry use cases need to be designed to meet industry-specific requirements for low latency, high bandwidth, reliability, availability, and security. SNs for 6G can enable wireless connectivity between manufacturing components, integrating wireless technologies into the manufacturing environment and requiring a new management system for coordination and routing.

The concept of a Cyber-Physical System (CPS) involves the integration of informatics, software components, mechanical and electronic parts to create a system with a high functional density. Its design incorporates sensors, actuators, connectivity, and computing power into a physical body with the goal of achieving a high degree of autonomy. This autonomy allows CPSs to respond appropriately in unknown situations, reducing the need for human monitoring and intervention while minimizing errors. Additionally, CPSs have the ability to collaborate, enhancing their range of functions, deployment options, and scalability of applications. Automated Guided Vehicles (AGVs) and autonomous mobile robots (AMRs) are an example of CPSs that operate independently and can be programmed to carry out specific tasks by sensing and reacting to their surroundings. AMRs may utilize Machine Learning (ML) algorithms, sensing, and localization methods to achieve tasks such as navigation, regrouping, scheduling, and resource allocation. These robots are equipped with sensors for localization and navigation and can be programmed to perform tasks such as collaborating with other robots for tasks like car assembly and transporting goods and materials. AMRs offer flexibility in mobility, autonomy, and perception ability. The focus of this use case is investigating collaboration scenarios for autonomous mobile robots to optimally perform common tasks in terms of quality, safety, and resource efficiency. One particular example is the use case of cooperative carrying AMRs, in the field of intralogistics and automation [28].

Sub-network description

Different building blocks of 6G can significantly enhance this use case, including digital twinning, ICAS, and 6G SNs. A reliable communication link is crucial for enabling collaboration between the AMRs. For instance, multiple AMRs that group together to fulfill a common task, like carrying a large object from one location to the other in a factory shopfloor, could form an ad hoc SN. The architecture shown in Figure 4 is representing most precisely how this use case can be deployed. During the lifetime of the created SN, the AMRs continuously exchange information (preferably in D2D fashion in order to save time) about the surroundings as well as the used communication resources, such as sensing and perception data, location and moving directions of neighboring AMRs and agents, used spectral resources in terms of frequency and time, etc. Furthermore, the interaction between several such SNs regarding their utilized radio resources as well as anticipated mobility patterns and advanced task management on SN-level, can be coordinated among the SNCs, again utilizing direct connection between them. The SNC of a Sub-network, in this use case, is represented via a designated AMR within the group.

However, sharing and accessing data among different AMRs introduces security risks that the 6G system must address. In a more centralized approach, a digital twin (DT) of the entire shopfloor could be made available to all AMRs connected to the SN, giving each participant a comprehensive view of the current environment. Achieving this would necessitate a close integration of the DT platform and the communication system to facilitate real-time data and knowledge sharing.

With the support of ICAS, the perception capabilities of each vehicle could be further enhanced by integrating information into the DT and applying sensor fusion. Given these requirements, a L2: Advanced autonomy (see Section II-B) is preferable for this use case. To complement the L2 autonomy of the SN, the CN needs to support a flexible interconnection between a SN and a PN. The respective network architecture suitable for realization of this use case is the one depicted in Figure 4. The AMRs communicate directly to each other (mostly on layer 2 due to the strict QoS requirements), exchanging real-time control states and required actions to carry a common object in the factory shopfloor from one location to the other.

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Requirements and KPIs

This particular use case involves strict requirements for reliability and latency, where the latency should be in the order of a couple of milliseconds (2-5 ms), and communication outages should be in the order of 10^{-6} - 10^{-8} [28]. The later one can be interpreted as a delay violation probability or the percentage of packets that are allowed to violate the target latency without jeopardizing the desired functioning of the CPS, and this usually depends on the design of the controller or the PLC of the AMR. As mentioned in Table IV, the requirements of the use case can also vary depending on the type of work piece, fragile or elastic, that the AMRs are carrying across the factory. For example, the fragile workpiece could be a large glass pane or wing of a windmill. On the contrary, an example of an elastic workpiece could be a big block of rubber that will not be damaged in case of little pressure or tension applied to it.

TABLE IV:
Performance requirements for cooperative carrying mobile robots in a factory [28]

KPI	Value (Fragile or Elastic)	Comment
Transfer interval	> 5 ms > 2.5 ms > 1.7 ms	First value: application requirement; Other values: more frequent transmission of information (2× or 3×)
Latency	< 0.5 × transfer interval	
User experienced data-rate	2.5 Mbit/s	
Communication -Service Availability	99.9999 % to 99.999999 %	
Communication -Service Reliability	~ 10 years	Mean time between failures
Survival time	0 transfer interval 2 × transfer interval	First value: application requirement; Other values: more frequent transmission of information (2× or 3×)
Message size	256-512 bytes	512 bytes with localization information
AMR/AGV speed	6 km/h or 12 km/h	
No. of AMRs/AGVs	2-8	
Service volume	10 m × 10 m × 5 m	Length × width × height. The SN might move throughout the whole factory site (up to several km²).

For communication, the AMRs should be able to support multicast communication in a device-to-device fashion as the AMRs are close together. To support the strict requirements of this use case there needs to be an evolution of device-to-device (sidelink) communication. An outlook on the impact on standardization and needed evolution in sidelink communication is discussed in Section VI. Each SN should occupy only the necessary resources for their spatial footprint to allow for high frequency reuse among SNs. The proposed approach for autonomous RRM on SN-level in Paragraph III-B is applicable to this use case, since a group of AMRs has a joint task with potentially different latency and reliability requirements than neighboring sub-networks. The strict latency and reliability requirements of this use case when exchanging the control states among the AMRs demand for more flexible RRM mechanisms on SN level and therefore with higher autonomy levels (e.g. L2), as described in Paragraph III-B. The AMRs should be equipped to handle the loss of internal and external communication and be able to act independently in case of interrupted communication with their peers or their environment or PN. The SN can be managed either centrally through a master AMR or in a distributed autonomous manner. The typical speed of the swarm is typically approximately 6-12 km/h.

Other Requirements to be considered for the collaborative and autonomous robots in factory use case:

- Campus Private Network or Network Slice from Public network needs to be set up at the environment to avoid intrusion from external network.
- ICAS needs to be adapted, specifically for route planning and collision/intrusion detection

Service Flow

In the context of the AMR/AGV use case, the service flows for the AMR/AGV entail several key processes. Upon receiving task assignments from an operator, who could be either an automated software or a human supervisor, the AMRs assess the need for collaboration. If collaboration is unnecessary, a Volunteer AMR (VAMR) steps forward to undertake the task, providing regular updates to the operator as per instructions. Conversely, if collaboration is required, an Owner AMR (OAMR) is designated, which then communicates task requirements to potential Helper AMRs (HAMRs). Following the formation of a SN comprising the OAMR and the selected HAMRs, separate resources are utilized to execute the task without interference to the primary infrastructure network. Throughout the task execution, the OAMR coordinates the HAMRs, facilitating information exchange and reporting task progress to the operator when necessary, utilizing both the infrastructure network and local communication links as appropriate.

C. Remote Aircraft Operation

Use case description

The mobility requirements of cellular communication systems users evolve with time. While in the past the focus was on supporting increasing velocities for terrestrial UEs, future communication systems like 6G need to consider mobility of airborne UEs [12]. A specific use case for aircraft cellular connectivity is remote operation for safe landing in emergency situations. Since RANs are widely deployed for terrestrial coverage, simultaneous service of airborne UEs through the same terrestrial network can be considered.

In this case a dependable command and control link needs to be established with guaranteed reliability, latency and throughput. Serving an aerial vehicle like a conventional terrestrial UE with moderate requirements might not be sufficient, so dedicated resources on the radio access and the CN level might be required.

One of the main challenges for this use case is the handling of the high mobility of aircraft. For example, passenger aircraft in approach to an airport, i.e., a maximum of 50 km away from the airport, can still reach velocities above the 500 km/h mark, which is the maximum that 5G is supposed to support. Particularly, the Doppler spread of the wireless channel can be challenging for conventional modulation schemes like Orthogonal Frequency-Division Multiplexing (OFDM).

Furthermore, if an airborne UE is supposed to be served by the existing terrestrial RAN infrastructure, i.e., base stations with antenna installations intended for terrestrial users, the proper handling of handovers becomes a critical task. While current handover mechanisms are built for moderate velocities of terrestrial UEs, much more frequent handovers for airborne UEs can be a challenge for the RAN.

Sub-network description

The remote operation use case does not require significant changes to the conventional RAN and CN architecture used for terrestrial communications. The aircraft to be remotely operated implements one or more UEs for remote operation, depending on the desired amount of redundant radio links. It is questionable if the high QoS requirements of this use case can be fulfilled just by very high priority scheduling of traffic in the RAN and CN. As a solution, using 6G SNs, deploying a dedicated SN infrastructure to separate local piloting-related traffic and generic PN-UE traffic, would result in improved general KPIs by a dedicated RAN, and (at least partial CN). Further, reliability could be increased, since a redundant CN would be in place. In addition, dual connectivity of UEs for remote operation to the SNC as well as PN could add further redundancy. Therefore, a (reduced) set of dedicated base stations, assigned to the SN and providing dedicated radio resources for communication could be a strong measure to fulfill these extreme use case requirements.

This is an example of L1 autonomy (see Paragraph III-B), since the operator RAN and CN provide full service and connectivity, but the SN in general is capable to maintain its basic operation in case of loss of connectivity to the PN. For this use case the PN-CN, as well as the SN-CN should handle sufficiently fast inter- Public Land Mobile Network (PLMN) handovers, so service disruptions across international borders or coverage gaps are mitigated. This might require an improvement of the AMF known from 5G networks or a new dedicated core NF, given the increased velocity of aircraft and increased interference from the terrestrial RAN.

Requirements and KPIs

The remote operation use case is closely related to the “Tele-Operated Driving” use case considered in the 5GAA Automotive Association [13]. The KPIs are summarized in Table V. The traffic in uplink (UL) direction, mostly consists of a video stream and telemetric data, which results in a moderate data rate. In downlink (DL) direction, the traffic will mostly consist of command-and-control data, which results in a rather low data rate. The data stream has a continuous (non-bursty) nature. Similar values for the data rates and latency are reported in [40] and [41]. The KPIs availability and reliability in this use case are derived from the reference values for remote control for process automation from [42].

TABLE V:
PERFORMANCE REQUIREMENTS FOR REMOTE AIRCRAFT OPERATION

KPI	Value
Geographical dimension	50 km (circular area around airport,≈ 7854 km²)
Number of nodes/UEs	1 or more UEs at one aircraft (dep. on desired amount of redundant radio links)
Reliability	99.999 %
Availability	99.999 %
UE Mobility	0- ~800 km/h
UE Altitude	0-5.000 m
End-to-end latency	10-100 ms
Data rate (DL)	300 kb/s
Data rate (UL)	25 Mb/s

Service Flow

SN service establishment due to an emergency situation:

- The aircraft pilot (UE-side) or ground assistance center triggers an emergency signal to issue remote assistance.
- The emergency notification is signaled to the other end of the remote assistance link, where a human carries out the remote operation.
- The PHY layer configuration for the link is switched from inactive/low priority to active/high priority.
- A SNC, e.g. located at the ground assistance center, establishes a SN with high priority scheduling (or even with dedicated resources) for remote assistance between the ground assistance center and the aircraft to be assisted.
- The core network prepares conditional handovers (CHOs) to ensure handovers with a lower chance of handover failures.

Sub-network operation during an emergency situation:

- The airborne UE periodically performs measurement reports, which are used for periodic CHO evaluations by the core network.
- If a CHO condition is fulfilled, a handover is performed, where the SNC performs a handover to a (potentially geographically far away) base station in the RAN.

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D. Airplane Onboard Services

Aviation operational data can be broadly classified into three main categories: Air Traffic Control (ATC), Airline Operations Centre (AOC), and In-Flight Entertainment (IFE) [28]. While ATC and AOC data primarily facilitate communication between the aircraft and, respectively, the control center and airline, IFE data refers to the transfer of media content to the aircraft and provides updates to existing onboard services [30]. The IFE-related services focus primarily on passenger entertainment, information delivery, and support for cabin crew operations.

IFE systems face significant challenges due to the bandwidth limitations of both satellite and air-to-ground backhaul technologies [31]. To overcome these constraints, a robust onboard system is essential for handling in-flight communication and content delivery. With millions of passengers flying daily, airplanes must rely on a sophisticated platform, capable of hosting and providing personalized services and content. Additionally, a secure and efficient network infrastructure is crucial to ensure seamless connectivity, safeguard data transmission, and increase the efficiency of crew member operations.

Existing air traffic management systems are far behind the capabilities of state-of-the-art technologies, such as 5G [29], and do not align with the anticipated architectures and components of 6G networks. In the context of 6G, IFE operations could effectively function as autonomous SN, operating in a partial autonomous mode during flight, providing real-time, in-flight resources and services for passenger, besides enhancing QoS for crew operations, communication, monitoring, and overall operational efficiency.

Use case description

The in-flight 6G SN has potential to support multiple heterogeneous services, including video on demand, games, personal device integration, shopping services, meal and beverage menus, crew-to-passenger messaging, and concierge assistance [30]. The SN must handle two main types of applications: first, those requiring flexible bandwidth and on-demand resource allocation, and second, critical services with guaranteed or pre-reserved resources to ensure continuous availability. The SN profits from a SNC that manages available resources and makes real-time decisions to balance service delivery. Both service types must be efficiently managed while ensuring safety and smooth service operation without interruption.

The first type of application is primarily associated with entertainment services within the subnetwork. These services, such as ultra-HD streaming and virtual reality experiences, often demand significant bandwidth. To address fluctuating passenger demands, the SNC must dynamically allocate resources, balancing high-demanding services with limited onboard capacity. The allocation must support both seatback monitors and personal devices.

To improve QoS, a robust caching system within the SN can reduce dependence on backhaul connectivity, which often suffers from high latency, limited bandwidth, and inconsistent availability. An onboard server hosts all airline-provided media content, such as videos, web services, gaming applications, and machine learning resources, while also temporarily storing content accessed by passengers' personal devices. This ensures uninterrupted service even during backhaul disruptions.

The caching system must accommodate the total number of users on the plane, including passengers and crew. To optimize backhaul usage, synchronization of the airline's exclusive content should be restricted to periods when the plane is parked. During flight, the SNC should regulate access to local cache and external application servers for content provisioning to personal end devices.

The second category of applications pertains to critical services, including aircraft monitoring, sensors, and control systems, and is very much related to the vehicular SN use case, introduced in Section V-A. These services are essential, and demand guaranteed resources to prevent lack of information for the pilot, delayed alerts, or even accidents. In both, commercial and military aircraft, monitoring systems handle a mix of safety-critical tasks, such as engine and flight control, and non-critical tasks like health monitoring and cabin management.

Traditionally, the monitoring systems rely on extensive, heavy wired connections, with sensor networks in an aircraft requiring up to 98.000 wires [32]. This creates significant challenges, including complex cabling, electromagnetic interference, sensor placement optimization, and ongoing maintenance. Integrating a 6G SN with wireless connectivity into this architecture can significantly reduce wiring requirements and weight, improving the monitoring system, efficiency, and security.

The monitoring services fall under narrowband IoT communications and align well with the massive Machine-Type Communications (mMTC) applications envisioned for 6G networks [33]. The SN must ensure frequent and reliable monitoring while processing all data locally within the aircraft, leveraging machine learning to avoid backhaul usage. Backhaul connectivity for these services should be reserved exclusively for communication between the pilot and the operations center.

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Sub-network description

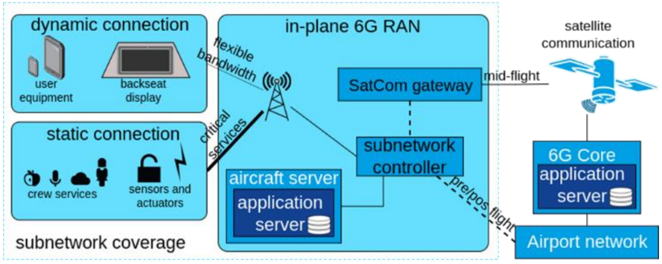

FIGURE 6 Envisioned onboard Sub-network deployment for an airplane onboard use case

Figure 6 illustrates an envisioned architecture for an onboard 6G-SN. This SN supports two types of connections: 1.) dynamic connections with flexible bandwidth, tailored for general entertainment services, and 2.) static or pre-reserved connections dedicated to critical services. Both types are managed by the local SNC.

When a service request is initiated, the SNC first searches the local application server for the required content before attempting to access external servers via the backhaul connection. If a connected UE requests content not present in the server, the SatCom gateway attempts to retrieve it from an external application server and download it to the aircraft server.

Upon landing, the SNC synchronizes the aircraft application server with external servers via the airport network. This ensures that the server remains up-to-date, and that all data collected during the flight, such as user experience metrics and flight monitoring information, is reported effectively.

Requirements and KPIs

TABLE VI:
PERFORMANCE REQUIREMENTS FOR AIRPLANE ONBOARD

KPI	Value
Number of nodes/UEs	Small aircraft: 100-240 Larger aircraft: up to 500
Required bandwidth for entertainment per display	Basic HD content: 2-5 Mb/s Demanding content: 10-20 Mb/s
Backhaul demand	Small aircraft: 300-720 Mb/s Larger aircraft: 1.5 Gb/s Larger aircraft + demanding content: 10 Gb/s
Required bandwidth for monitoring	Sensors: 1-10 Kb/s Video-based sensors: 1-10 Mb/s Radar systems: up to 100 Mb/s

Table VI provides performance requirements for various aircraft sizes and content types including HD content for entertainment and more demanding applications, including 4K video or high-frame-rate gaming. The number of seatback displays depends on type of aircraft and seat configuration.

For airplane sensors and monitoring systems, bandwidth needs are relatively modest by comparison. Most sensors require 1-10 Kb/s, with video-based sensors demanding 1-10 Mb/s and radar systems reaching up to 100 Mb/s, depending on resolution and refresh rates.

However, the envisioned backhaul solutions for satellite communications remain insufficient to fully support the comprehensive bandwidth demands of a large airplane. For example, the average throughput of laser communication in Starlink constellations [34] ranges from 1.8 to 10 Gb/s, while the throughput per cell in the European Aviation Network [35] is estimated at 75 Mb/s per cell. These requirements highlight the gap between current satellite communication capabilities and the total throughput required for modern in-flight entertainment and monitoring systems, especially in larger aircraft with demanding configurations.

Service Flow

Requesting a service available in the onboard server:

- A passenger requests an ultra-HD video from the in-flight entertainment system.
- The SNC retrieves the requested content from the onboard cache.
- The SNC allocates radio resources to deliver a seamless viewing experience.
- No backhaul connection is needed, ensuring efficient resource usage.

Requesting a service, not available in the onboard server:

- A passenger connects their personal device to the onboard SN.
- The passenger requests access to an online shopping service not cached locally.
- The SNC attempts to fetch the required content through the SatCom gateway, retrieving it from an external server via the backhaul connection.
- The content is then temporarily stored on the aircraft server for the duration of the flight.

Collecting monitoring data

- Onboard sensors continuously monitor critical systems like engine performance and cabin conditions.
- The collected data is processed locally using a machine learning solution to detect anomalies or optimize system performance.
- Feedback is provided to the pilot or crew in real time, enabling proactive adjustments and enhancing operational efficiency.

E. Emergency Services

Use case description

Use cases for public safety in wireless networks typically address loss of coverage or insufficient capacity. The following paragraph describes a use case, where firefighters arrive at an emergency scene without sufficient coverage: A fire has broken out in a building. The emergency services arrive at the scene, by one or several vehicles. To explore the area and enable an assessment of the situation, one or more teams consisting of two firefighters each, enter the building.

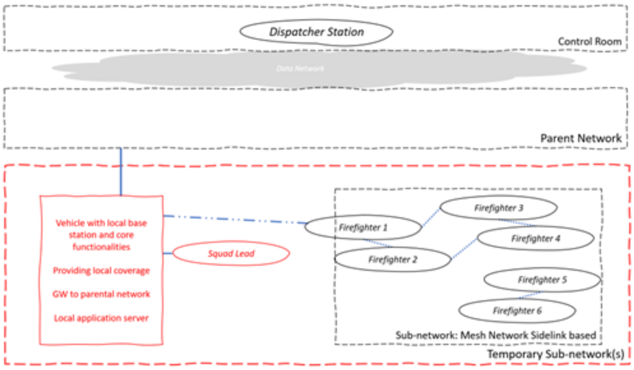

FIGURE 7 Different forms of SNs in an emergency use-case.

There is poor radio coverage outside of the building and no radio coverage inside of the building. For mission critical communication, the fire brigade uses Mission Critical Communication Services (MCX), as defined by 3GPP [26]. Mission Critical Push Talk (MCPTT) is considered as backbone of mission critical communication. Further, Mission Critical Data (MCData) and Mission Critical Video (MCVideo) and associated applications are used to enhance situational awareness of the squad lead and the control center. To provide coverage, one vehicle is equipped with a local base station and core functionalities, acting as a SNC, to enable local communication and to provide a backhaul (e.g. via satellite) to the central communication system, which is connected to the control center. While the firefighters enter the building, they may lose connection to the base station. To mitigate this, the UEs of the firefighters form a mesh network, relaying the communication to the SNC, using device-to-device communication links.

If the local network loses connection to the central communication system, provided by the PN, local MCPTT, MCData and MCVideo Services are still available. Also, authentication and security procedures are available to allow newly arrived members access as well. Common Services Core functions (e.g. Group Management Server) are not required while being without connection to the central communication system and will not be performed during the lifetime of the temporary local network.

Sub-network description

During the mission, a temporary SN with L1 autonomy level (see Paragraph III-B) is set-up, consisting of the local SN gNB and CN functionalities on the vehicle and a number of SN-UEs located around the vehicle and outside the building. Strictly speaking, with the UEs building a Mesh Network in the building and the local SN, two SN types are being created and used. Internal, the UEs are connected to the SN gNB as direct links (Squad Lead and Firefighter 1 in Figure 7), indirect links via the Mesh-Network to the base station (Firefighter 2, 3 ,4), or off-network (Firefighter 5, 6) in Device-to-Device communication. External, the local core functionalities provide a backhaul link to the PN.

Requirements and KPIs

The summarized requirements (see Table VII) are stated by Heikkilä as requirement for mission critical communication in her study of Tactical Bubbles [27].

TABLE VII:
REQUIREMENTS FOR "TACTICAL BUBBLES" [27]

Communications Type	**Requirement Category**	**Identified Requirements**
Generic	Availability	99 to 99.999 %
	Startup time	0 to few minutes
	Configuration efforts	no configuration
Combined user traffic	DL per user	50 Mb/s
	UL per user	25 Mb/s
Push to talk	Delay	75 ms
Group video	Delay	100 ms

Service flow

The following paragraphs show possible service flows which might arise during a mission:

Service flow, when the SN is connected to the PN:

- UEs connect to the Application Server over the 6G network. UEs can use MCData, MCPTT and MCVideo services to communicate and collaborate with each other through the Application Server.
- The database connected to the Application Server is used to store data during operation (call statistics, configuration data, call logs and recordings).

Service flow when the SN is disconnected from the PN:

- UEs detect the missing connection to the Application Server and ask the SNC for help.
- SNC detects the missing connection to the PN.
- SNC queries the local NFs to forward traffic from UEs within the SN to the local Application Server.
- UEs now communicate via the local Application Server, which provides similar services to the global Application Server (MCData, MCPTT and MCVideo).
- A local database is available that is connected to the local Application Server and is used to store the service-related data and a copy of the configuration-related data

Service Flow when the SN reconnects to the PN:

- SN detects the availability of the PN.
- The local and global database synchronization is in progress. The global Application Server is informed of the interruption.
- The UE traffic is redirected to the global Application Server.
- UEs now communicate with other UEs via the global Application Server.

Post conditions:

- The services offered to the UEs were available even when the SN was not covered by the PN.
- The transition from the global Application Server to the local Application Server and back to the global

Application Server took place without interrupting operations, i.e. The emergency services were able to use MCData, MCPTT and MCVideo throughout the operation, regardless of the connection to the PN.

- Subsequently, the data logged during the operation was present in the global database

VI. STANDARDIZATION IMPACT

In this section we analyze existing standardized technologies and their similarities with SN concept explained in this paper. Moreover, we highlight specific area of differences that can be studied further and brought to the standardization forums.

A. Non-Public Networks

In the concept of Non-public Networks (NPNs) in 5G, e.g., driven in the industrial context [14], network services are offered to a private group e.g., in a localized campus area. NPN is the most similar concept to 6G SN as it offers specialized, on-premise communication, with network control and optimization tailored to customers' needs. NPNs may be deployed as isolated standalone networks or integrated within a public network. A standalone NPN contains RAN, CN and the transport network within the premise and enables a completely independent network. In contrast, a public network integrated NPN depends on the public network for some of the NFs located in the CN. The degree of dependence balances a tradeoff between cost, performance, and privacy. The major differences between the SN and NPN is that the SN use cases require more flexibility to adapt the more diverse set of requirements with less complexity. Moreover, the mobility of the entire SN goes beyond what is considered for NPN creating novel challenges e.g., interference management.

On the other hand, the Layer 3 routing proposed in Section III-IV relies on principal UE technology to create a link that acts as backhaul between SN and PN. The IP routing then is proposed to enable intra-SN or inter-SN and PN communication. In addition to simplicity, SN-to-SN and SN-to-PN coordination can be already realized using the existing RAN coordination. The SN coordination creates unique challenges, e.g., interference management for moving SN, and further optimizations in radio resource coordination in the context of SN can be studied. Another improvement area is to study optimization of the SN backhauling solution that is based on Layer 3 relaying. Depending on the use case requirement the performance of the Layer 3 relaying solution can be studied for further identification of improvement areas.

B. Integrated Access and Backhaul

Integrated Access and Backhaul (IAB) has been introduced in New Radio (NR) as an alternative to expensive fiber backhaul to extend the coverage of the cellular network. In Release 16, the baseline for IAB-based relaying was established. IAB related node protocol stacks are based on the gNB-CU/-DU split architecture, with the gNB-internal F1 protocol in between CU and DU [43]. In Wireless Access and Backhaul (WAB) there is no split in a gNB while in IAB benefits from gNB split (gNB-DU). As a consequence, the Backhaul (BH) connection in IAB is transporting F1. IAB has an IAB-specific BH protocol, Backhaul Adaptation Protocol (BAP) inserted in the standard UE and gNB protocol stacks. BAP has flexible routing functionality (on BAP layer) enabling different multi-hop topologies (similar to directed acyclic graphs). The F1-termination (of the IAB-DU) is in a separate node (in the gNB-CU of the IAB-donor). Based on UE mobility procedures, Release 16 and Release 17 allowed intra- and inter-IAB-donor mobility of the IAB UE function, respectively. Release 18 introduced IAB-node mobility (by introducing quasi F1 mobility), assuming only single-hop topologies. As a result, the IAB UE function's Radio Resource Control (RRC) connection and the IAB-DU's F1 connection can be independently terminated and changed to separate IAB-donor-CUs. F1 is not designed to have features like intermediate termination or local breakout. As a result, IAB operates as a closed system. IAB-nodes need an IAB-donor node and can only communicate with other relevant entities defined in the scope of IAB (i.e., having the BAP layer). Thus, with a node architecture like IAB it is not clear how the required SN functions can be flexibly introduced as part of the SNC as any IAB-DU CP traffic or any traffic from a 6G UE or a device served by the SN cannot be terminated before the PN (hosting the PN gNB to be implemented equivalently to an IAB-donor). A SNC based on an IAB-node requires complex procedures to break out from a so far closed protocol system. Thus, this would require significant and SN specific standardization impact.

C. Wireless Access and Backhaul

While being very feature rich, IAB also comes at high implementation complexity and was therefore not commercially launched by any vendor. Instead, 3GPP standardizes Wireless Access and Backhaul (WAB), that allows multi-hop deployments with much less implementation effort [18]. Radio resource management can be considered within WAB, but typical implementations work without it. A baseline WAB deployment does not require complex feature implementation in network equipment but can be deployed with current ones, as it leverages on the capabilities of the IP Layer. As of current 3GPP timeline plans, IAB standards will not be evolved. Unlike IAB, the WAB is based on already standardized and more importantly implemented building blocks and protocols and hence is expected to require minimum standardization effort. A WAB node is assumed to consist of a WAB gNB and a WAB UE function (based on the standard UE protocol stacks). The BH connectivity (for the NR Next Generation (NG) connection) of the WAB gNB is based on standard Protocol Data Unit- (PDU-) sessions between the WAB UE function and a BH UPF (simply substituting the usual wired BH IP connection). WAB is not limited to using a UE for BH purposes. 3GPP has adopted that the use of other types of backhaul, e.g. non-3GPP backhaul, is up to implementation [19]. Thus, there is minimum dependency between the WAB gNB and WAB UE function. For some CP procedures, it is expected that the SN requires connectivity to the PN. Thus, in case of unavailability of the PN and depending on the level of autonomy (see Paragraph III-B), a minimum set of subnetwork functions need to be specified or reused to ensure service continuation for subnetwork devices. It should be possible to locate certain, use-case specific, subnetwork RAN functions as close as possible to, or as part of the SNC and/or close to the PN RAN function (e.g., parent gNB). The current 5G Core supports selective traffic routing to a local DN through "Single PDU Session with multiple PDU Session Anchors" (the technical 3GPP term for a local UP breakout implementation). It is expected that this together with the independence of WAB gNB and UE function is a good template and support basis for a 6G SN architecture support and specification. Depending on the use case, e.g., emergency services, the WAB standardization might need to study and address enhancements for realization of multiple topologies.

D. Sidelink Communication

The standardization of over-the-air transmissions in 3GPP prior to Long-Term Evolution (LTE) Release 12, mainly focused on the link between UE and base station, i.e., eNB. The backhaul link within the relaying context was standardized in Release 10, assuming that a relaying node operates in-band and in half-duplex mode [37]. With the growing demand for device-to-device (D2D) communications, 3GPP began to investigate and define D2D in Release 12 [38], which was subsequently developed into vehicle-to-everything (V2X) through the Sidelink. Release 14 introduced the support for LTE-V2X followed by 5G-NR V2X support in Release 16. The V2X standardization in LTE and 5G NR is frequently known as cellular V2X or C-V2X. In LTE-V2X, Sidelink expanded to include vehicle-to-everything (V2X) use cases, supporting communication between vehicles, pedestrians, network and infrastructure. LTE-V2X also introduced features like autonomous radio resource allocation based on sensing and congestion control. In 5G NR-V2X, Release 16, for Sidelink in-addition to broadcast, unicast and groupcast is supported. Higher modulation coding schemes and Multiple Input Multiple Output (MIMO) transmissions are supported to improve spectral efficiency. In Release 17, 5G NR-V2X, the focus was on power saving and enhanced resource allocation using features like inter-UE coordination. For power saving two features are defined, partial sensing and Sidelink discontinuous reception. In Release 18, NR-Sidelink further evolves to support carrier aggregation, operation in Frequency Band 2 (FR2) spectrum, relay enhancements as well as Sidelink positioning and ranging [38].

The standardization work for 5G NR-Sidelink up to and including Release 18 primarily aimed to address the latency and reliability needs of automotive and public safety applications, which are not as stringent as those for factory settings. As we move towards 6G, 5G NR-Sidelink has the potential to broaden its functionalities beyond traditional vehicle-related use cases, enabling new use cases like aerial networking or industrial manufacturing with flexible architectures. Additionally, 5G NR-Sidelink does not accommodate URLLC requirements, therefore these requirements can be addressed within 6G [39]. Thus, a Sidelink multi-hop relay can help with enhancing coverage and spectral efficiency, enabling dynamic SNs. In addition to the single-hop relaying already standardized by 3GPP, multi-hop relaying can allow UEs and Unmanned Aerial Vehicles (UAVs) to form mesh network topology within SN for diverse applications and use cases. It can also improve reliability, by introducing redundancy and sending the packet via two separate (potentially multi-hop) paths to its destination UE. A Sidelink relay can help in enhancing coverage and spectral efficiency, enabling dynamic SNs.

Additionally, RRM which is crucial for the 5G-NR Sidelink, also needs to advance further. A distributed RRM, where resource allocation is initiated by a UE, could play a critical role in new industrial applications involving D2D communication, such as cooperative autonomous robots. Incorporation with ICAS could be one of the ways to enable distributed RRM. This approach could potentially transfer resource allocation decisions closer to the SN device, where the context of joint tasks and the environment can inform the necessary communication resources. Also, the UE could potentially manage resources for another UE, and similarly, the SNC could assume this responsibility in use cases or scenarios where it is beneficial.

VII. CONCLUSIONS & WAY FORWARD

A. Conclusion

In this paper, we provide a contribution on specifying the term of 6G SNs, starting with a comparison of the concept to existing networks out of the 5G era. Further, the broad variety of potential SN types is classified mainly from two perspectives, a) Core Network involvement and b) autonomy of a SN.

Based on these classifications the paper proposes an architecture framework, developed from a 5G starting point, and is giving alongside explanations on SN autonomy, scalability, robustness, and application awareness. The proposed architecture framework supports SNs to operate independently or in conjunction with PNs, depending on their autonomy level.

Further the paper identifies and describes a diverse range of use cases for SNs, including in-vehicle communication, robotics, in-flight entertainment, emergency services, and remote operation of aircraft. The main contribution here, is a unified description with respective KPIs, demonstrating the versatility of SNs, that can be seen as a summary of different industry needs.

Finally, gaps in standardization are identified, particularly in relation to 3GPP standards. Thus, steps for a clear

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technological definition and standardization towards future implementation of SNs can be derived.

B. Way Forward

This paper sketches a range of potential directions in which the topic of local, high-performance communications might evolve with the upcoming steps towards 6G. Despite pointing out relation of the novel concept to existing ones, definition of architectural system designs, and description of future use cases, there are many more steps required in near future in order to do come to a widely adopted and clearly defined technology.

An obvious consecutive step would be the systematic numerical analysis and comparison of theoretically achievable KPIs, based on proposed architectural approaches. Further, the authors of this paper already work on different implementations of Proof of Concepts to evaluate proposed ideas together with applications and use cases and would like to engage others to do so on their domains to allow for verification and comparison with expected results and simulations. Basic implementations could already be done with standard 5G components, since the proposed Sub-Network architecture is designed to allow for incremental integration into existing networks, where basic functionalities can be achieved without immediate changes to mobile core components, but full-fledged utilization and optimization of its advanced capabilities would necessitate modifications and novel implementations within CN components, while maintaining compatibility with existing interfaces through their adapted usage.

Nevertheless, consolidation across relevant vertical industries might be necessary to identify a mainstream for standardization and implementation. Lastly, a survey on the Mobile Network Operator-perspective on roll-out scenarios would be needed, also covering potential spectrum-licensing aspects.

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