



Open 5G campus networks: key drivers for 6G innovations

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Abstract 5G was designed to enable and unify Industrial Internet communication. Emerging 5G campus networks, in particular, provide a flexible communication infrastructure option addressing the specific needs of industry verticals regarding low latency, resilience, security, and operation models. Network Function Virtualization (NFV) and Edge Computing have paved the way for vendor-independent, customized, and scalable network designs for the past decade. Today, Open Radio Access Network (Open RAN) principles extend this architectural thinking toward an innovative and open 5G end-to-end infrastructure. 5G campus networks, in particular, might benefit from this envisaged openness. One key driver for boosting the global interest in private campus networks was the allocation of a dedicated 5G spectrum in Germany in 2019. In addition to permanent spectrum allocations for static campus network deployments, nomadic ad hoc campus network deployments using novel mechanisms, such as dynamic spectrum access and trading, also emerge. Both network types are enabled by the inherent flexibility of combining or disaggregating the desired open 5G RAN and core components in appropriate network deployments. Building upon years of experience in developing and operating 5G network cores and 5G testbeds, the authors provide an overview of the emerging global campus network market, available spectrum options, use cases for nomadic campus network deployments, and the need for open campus networks and open end-

to-end technology testbeds. Utilizing the Fraunhofer FOKUS Open5GCore, the 5G Playground testbed, and the 5G+ Nomadic Node as examples, the paper sketches a blueprint for campus networks for international, applied research and development. Ending with an outlook on the evolution of campus networks, namely the transition toward higher spectrums and the integration of non-terrestrial networks, but also the adoption of more agile software principles and the deeper integration of AI/ML technologies for network control and management, it will become obvious that open campus network innovations will pave the way toward 6G.

Keywords 5G · 6G · Campus networks · Private networks · Industrial Internet · Nomadic networks · Open RAN · Open testbeds

Offene 5G-Campusnetze: Schlüsseltreiber für 6G-Innovationen

Zusammenfassung 5G wurde entwickelt, um industrielle Internetkommunikation zu ermöglichen und zu vereinheitlichen. Insbesondere die neu entstehenden 5G-Campusnetzwerke bieten eine flexible Kommunikationsinfrastrukturoption, die den spezifischen Anforderungen der Branchen in Bezug auf niedrige Latenz, Ausfallsicherheit, Sicherheit und Betriebsmodelle gerecht wird. Network Function Virtualization (NFV) und Edge Computing haben in den letzten zehn Jahren den Weg für herstellerunabhängige, kunden-spezifische und skalierbare Netzwerkdesigns geebnet. Heute erweitern die Prinzipien des Open Radio Access Network (Open RAN) dieses architektonische Denken in Richtung einer innovativen und offenen 5G-Ende-zu-Ende-Infrastruktur. Insbesondere 5G-Campusnetze könnten von dieser angestrebten Offenheit profitieren. Ein wichtiger Treiber für die Steigerung

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des weltweiten Interesses an privaten Campusnetzen war die Zuweisung von dediziertem 5G-Spektrum in Deutschland im Jahr 2019. Neben dauerhaften Frequenzzuweisungen für statische Campusnetzbereitstellungen entstehen auch nomadische Ad-hoc-Campusnetzbereitstellungen, die neuartige Mechanismen verwenden, wie z.B. dynamischen Frequenzzugang und -handel. Beide Netzwerkarten werden durch die inhärente Flexibilität ermöglicht, die gewünschten offenen 5G-RAN- und Kernkomponenten in geeigneten Netzwerkimplementierungen zu kombinieren oder zu disaggregieren.

Aufbauend auf jahrelanger Erfahrung in der Entwicklung und im Betrieb von 5G-Netzwerkernen und 5G-Testbeds bieten die Autoren einen Überblick über den aufstrebenden globalen Markt für Campusnetzwerke, verfügbare Frequenzoptionen, Anwendungsfälle für nomadische Campusnetzbereitstellungen sowie die Notwendigkeit offener Campusnetzwerke und offener Ende-zu-Ende-Testbeds. Am Beispiel des Fraunhofer FOKUS-Open5GCore, des 5G Playground Testbed und des 5G+ Nomadic Node skizziert der Artikel einen Entwurf für Campusnetzwerke für internationale, angewandte Forschung und Entwicklung. Abschließend liefert er einen Ausblick auf die Entwicklung von Campusnetzen, nämlich den Übergang zu höheren Frequenzen und die Integration nicht-terrestrischer Netze, aber auch die Übernahme agilerer Softwareprinzipien und die tiefere Integration von KI/ML-Technologien für die Netzsteuerung und -verwaltung. Es wird deutlich, dass Innovationen für offene Campusnetze den Weg zu 6G ebnen werden.

Schlüsselwörter 5G · 6G · Campusnetze · Private Netze · Industrial Internet · Nomadische Netze · Open RAN · Offene Testbeds

1 Introduction

The digitalization of industry requires a network communication infrastructure specific to industrial needs. Open communication network architectures play a key role here, by enabling innovation and competition among verticals, while at the same time being a corner stone for a European digital sovereignty. Therein, Open Radio Access Network (RAN) is a consequent continuation of network function virtualization (NFV) for open end-to-end network architectures. Open RAN takes advantage of the ongoing business trend of virtualization providing the technological enabler for the dynamic provisioning of scalable end-to-end solutions. In particular, the potential to virtualize parts of the radio network suits well the ongoing trend towards private or edge-based cloud infrastructures versus exclusively relying on public cloud services.

Such private campus networks thus can potentially be “a hybrid network that combines both Third Generation Partnership Project (3GPP) and non-3GPP access and operating models” and corresponding radio

access technology [1]. While opening numerous business opportunities, the complexity of the 5G value chain constantly increases and must consider a growing number of actors in the 5G market. As such, 5G campus networks are a global phenomenon for various market segments.

Fraunhofer FOKUS has been looking at 5G network core architectures and 5G testbeds since 2015. With its Open5GCore [2] and 5G Playground [3], FOKUS has provided an experimental platform and trial environment for R&D and industry, thereby circumventing the initially slow rollout of 5G stand-alone networks. As such, 5G local campus networks are one solution for immediate, need-based deployment of industrial 5G networks [4]. Campus networks “will be a combination of evolution and revolution” of industrial networks [5], while the market shifts towards an open eco system and flexible business models [6, 7].

This paper draws on the authors’ many years of experience in prototyping local and public telecommunication networks. It targets the global landscape of 5G campus and private networks; recaps the market view for campus networks, available spectrum options; and derives from there the growing demand for nomadic 5G networks and open testbeds. From there, the paper highlights the Fraunhofer FOKUS Open 5GCore and the 5G Playground as a reference implementation for testbeds, which provide via the FOKUS 5G+ Nomadic Node a fully portable, autonomous 5G deployment suitable for research, development, and trials of implementation of considerations for local 5G and beyond networks. The paper concludes with an outlook on the future of 5G campus networks focusing on related aspects on nomadic networking, Open RAN based architectures, and beyond 5G and 6G networking aspects.

2 Global landscape of 5G campus and private networks

2.1 Market view

Over the last years, especially since the opening of 5G spectrum for private use, the market for 5G campus and private networks had been continuously growing and became a second major market segment for 5G technology in addition to the traditional telco-provider-oriented market segment [8]. While private campus networks provide connectivity in a geographically constrained environment exclusively to a constrained set of users, they may be deployed and operated privately, i.e., by the organization connectivity is provided for, or by an external company or even network operator.

While the market is expected to continuously grow, private “5G networks are increasingly becoming the preferred approach to deliver wireless connectivity for critical communications, industrial Internet of Things (IIoT), enterprise & campus environments, and public

venues,” reaching by 2023 compound annual growth rate (CGAR) of USD 8 billion [9]. While the market segments for private 5G networks are very diverse, four verticals dominate, namely: manufacturing and factories, energy and utilities, transportation and logistics, and defence. We see that private 5G campus networks address the needs of those markets and feature comprehensive end-to-end security across organizations as they inherently allow to shield information and infrastructure from externals and threads [1, 8]. As such, we see a clear global market trend towards private 5G campus networks. Providing high throughput, low latency, and high reliability, campus networks will “accelerate the growth and expansion of telecom” [10]. With that, the market trends towards an open eco system for 5G campus networks enabling flexible business models for providing hardware, software, and services.

2.2 Spectrum view

Germany was one of the pioneers and main incubators for private 5G networks by dedicating 100 MHz of the 5G spectrum exclusively for private use. While 300 MHz of 5G spectrum were auctioned to public telco operators, obtaining spectrum for private, local campus networks is rather affordable. For example, a “10-year frequency assignment of 30 MHz for an area comprising 25 ha (500 m × 500 m) would accordingly cost €3250 (residential area), which corresponds to an annual fee of €325.” The use of the spectrum grant is bound to the boundaries of the grounds owned or leased by the applicant [11]. In addition, the 26 GHz spectrum is also made available for local fixed communication networks in Germany. In contrast to the sub-6G bands, the assignment is not bound to owners of the local grounds, but the active usage of the spectrum must be proven after 12 months [12].

Alternatively, to static assignments of spectrum, the *neutral host* concept allows to temporarily lease spectrum owned by public telco providers. Herein, a private network operator or company—the *neutral host*—only investing in radio infrastructure such as base stations does not own spectrum but either leases its infrastructure to multiple service providers or leases spectrum from one public service provider [13]. Such long- or short-term lease of spectrum may enable private campus network deployments in countries not having allocated 5G spectrum exclusively to private users, but also enables rapid ad-hoc deployments of 5G networks at locations where the private network provider does not own the grounds where the network is deployed. This concept of temporal spectrum leasing is like Citizens Broadband Radio Service (CBRS) in the United States, where one may lease spectrum owned by other entities as secondary users if it is not actively used. Table 1 summarizes the available sub-6 GHz spectrum [14]. While bands

Table 1 Spectrum allocation for several countries and regions [14]

Region	Band (spectrum)
USA	n48 (3550–3700 MHz)—CBRS n96 (5925–7125 MHz)—unlicensed band
Germany	n77/n78 (3700–3800 MHz)—licensed for private use
France	n38 (2570–2620 MHz)—licensed for private use
UK	n77 (3800–4200 MHz)—licensed for private use
European Union	n96 (5900–6400 MHz)—unlicensed band
Japan and China	n79 (4400–5000 MHz)—licensed for private use
South Korea	n96 (5925–7125 MHz)—unlicensed band

n48, n77/78 and n79 are for 5G networks, band n96 is shared between 5G devices and WiFi-6 devices.

2.3 Use cases and the rising need for nomadic networks

Campus networks are often classified into two main categories: static deployments and nomadic deployments. Static deployments are typical for providing network communication to enable a specific business context for industrial Internet use cases. On the other side, nomadic deployments are found whenever campus networks have to be deployed for frequently changing locations for which a permanent, static deployment is not cost efficient. In the latter class, 5G nomadic networks address the demands of several use cases, such as safety, agriculture, and construction sites. As such, nomadic and static 5G campus networks complement each other to address a wide spectrum of market relevant use cases [1].

2.4 Towards open campus networks and the need for open end to end technology testbeds

Coincidentally with the political desire for digital sovereignty in critical infrastructures and the resulting push for Open RAN based infrastructures, there is a technological need for modular and scalable Campus Network deployments driven by different business and operation models to meet the demands of dedicated vertical domains. In the future, enterprises will need high flexibility to integrate 5G connectivity into their existing and future business and are starting to recognize that connectivity is constantly evolving, leading them to adopt more agile DevOps principles in their ICT divisions.

It becomes clear, that multi-vendor campus network deployments will become the new standard to assure flexibility and vendor independence. Very likely, 5G open-source software initiatives will augment or even speed up this movement. This will lead to a new eco system for open campus networks in the mid- to long-term but requires corresponding testbeds in order to assure the interoperability of the components of different suppliers and the performance, security, and resilience of the integrated

solutions. Germany is taking a pioneering role in this effort [7, 15–18].

3 The 5G playground as a blueprint for campus networks R&D

3.1 The Open5GCore—a reference implementation for Open 5&6G networks

3.1.1 Considerations for building local 5G networks

As compared to public telecommunication provider networks, private local 5G networks are in general deployed in a smaller environment having less coverage and less connected devices. Also, they may be administrated like private WiFi networks, i.e., the owner of the campus is most likely at the same time the administrator of the network. Depending on the operational provider model, such local 5G networks may be built utilizing dedicated slices of external public 5G networks, dedicated local network deployments, or hybrid half-and-half schemes combining the two approaches. Table 2 summarizes the characteristics of the three deployment options. Depending on the deployed option, only parts of the service-based architecture (SBA) of the network core are required, thus demanding a fully modular network core design to accommodate either option.

3.1.2 Open5GCore Release 7

The Open5GCore developed by Fraunhofer FOKUS prototypes the 3GPP Rel. 15 and 16 5G System (5GS) core network functionalities. Available in source code, it is interoperable with 5G New Radio (NR) base stations and user equipment (UE), which makes it most suitable for R&D activities and testbed deployments for trials and pilots, and for the further development of new beyond-5G and 6G standard-oriented functional features. In a campus network environment, the Open5GCore enables a fast and targeted 5G innovation, hands-on fast implementation, and realistic evaluation and demonstration of new concepts and

use case opportunities. Due to its modular design, it enables any deployment option of a campus network. Key features of Open5GCore Rel. 7 include:

- Fundamental 5G core network functions [19]:
 - Access and Mobility Management Function (AMF)
 - Session Management Function (SMF)
 - Authentication Server Function (AUSF)
 - Unified Data Management (UDM)
 - Network Repository Function (NRF)
 - User Plane Function (UPF)
- Implementation of the 5GS Service Based Architecture [19]
- Integration with standard 5G NR using the 5G interfaces (N1, N2, N3) [20, 21], 5G Non-Access Stratum (NAS) and NG Application Protocol (NGAP)
- Implementing control-user plane split (CUPS) with Packet Forwarding Control Protocol (PFCP) (N4) [22]
- Advanced Quality of Service (QoS) and session management with traffic influence with the Policy Control Function (PCF)
- Network slice support through the Network Slice Selection Function (NSSF)
- Comprehensive non-3GPP access convergence provided by a Non-3GPP Interworking Function (N3IWF)
- Location Service Support based on Location Management Function (LMF) and Gateway Mobile Location Center (GMLC) [23]
- Benchmarking Tools and UE & RAN simulators

The consequently modularized implementation of the service-based architecture (c.f. Fig. 1) as well as the capability of the Open5GCore to run on top of common hardware platforms and its ability to be deployed within containers, pods or virtual machines on top of a large number of virtualization environments, [2] allowed the Open5GCore to become a reference implementation for 5G testbeds and portable 5G deployments.

The development of Open5GCore was inspired by the need to have a homogeneous, cloud-native code

Table 2 Comparison of 5G campus network deployment alternatives

	External network	Dedicated network	Half-half network
Deployment	Together with the public network	Dedicated for the specific location	Dedicated for the specific location
Coverage	The same as the public network	Customized for the dedicated environment	Customized for the dedicated environment and harmonized with public network
Services	Through the operator network (may be edge)	Deployed mainly on-premise	Mix of operator and on-premise services
Authentication and authorization	Through the public network	Through the local network	Depending on the user entity (UE) identity used
Access control	Fully operator controlled	Shared with the local network management	Mixed between full operator control and shared with local
Privacy	Same as virtual private network (VPN)-type of services	Localization of the services	Depending on the UE identity used
Mobility	Full mobility with special zones	Local support with external “roaming”	Depending on the UE identity used
Network management	Network operator	Shared or only local admin	Shared with local admin

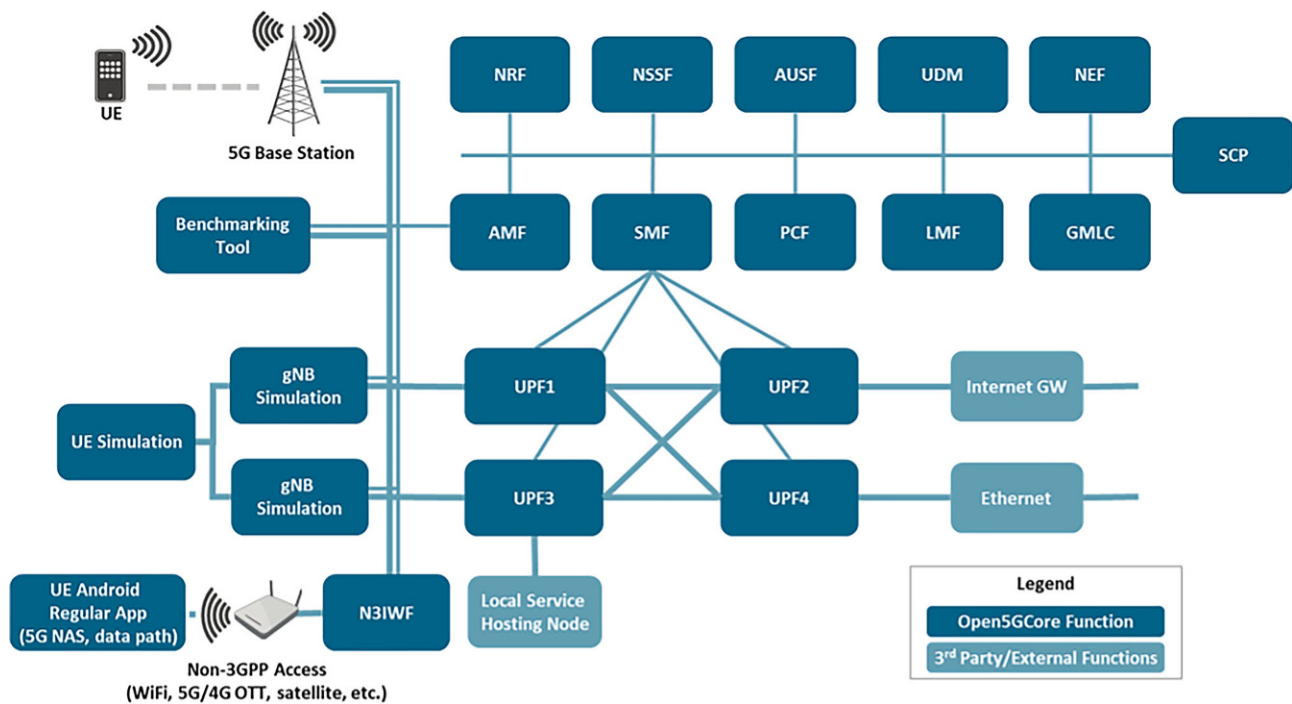


Fig. 1 Open5GCore architecture

base for realizing the main 5G core network features and being able to adapt and extend this code to specific research and development questions. Having already had experience developing virtualized 3G and 4G network software throughout the past two decades at Fraunhofer FOKUS, it was straight forward to start the Open5GCore software project in 2016, considering the absence of any other 5G core network implementation. It is important to stress that Open5GCore is neither an open source project nor a product. Its unique selling point is that it has been developed to be licensed by academia and enterprises for scientific and industrial testbed purposes, respectively. It is therefore very difficult to compare Open5GCore with the existing and emerging 5G core networks. Particularly, as the number of providers is constantly increasing due to the fact, that the rise of “open” 5G network infrastructures, motivated by the international Open RAN hype, and Rakuten’s approach to provide 5G in Japan, is creating a new eco system of core network providers. This trend is further supported by the rising interest in campus networks, which demand a high degree of network customization. Already, the global core network ecosystem includes diverse solutions such as

- currently available large-scale service provider network products from the established network equipment vendors, such as Nokia, Ericsson, Huawei, Samsung, etc.
- new network software companies, like Mavenir [24], NEC [25], Rakuten [26], Athonet [27]

- emerging hyperscaler hosted core network platforms offered as network as a service, such as AWS [28], Google [29, 30], IBM [31], Microsoft Azure [32], Oracle [33], etc., or
- open source 5G core network projects [34], like free5GC [35] from the Open Networking Foundation, OpenAir Interface’s CN [36] supported by Eurecom, MAGMA CN [37] from the Linux foundation and Open5GS [38]

The first three categories represent quite expensive, proprietary core network products, i.e. software which could not be adapted and extended by the user/enterprise for specific vertical application needs. Available open source projects suffer from the classic challenges in open source developments, such as code quality and consistency in the various software packages originating from different programmers, constant feature change and lack of integrated testing, inconsistent quality of documentation, uncertainty in regard to future development activity, as well as a lack of commercial support and SLAs, unless there is an established (commercial) distributor driving the development. However, it is probably the latter group of open source projects, which are closest to the Open5GCore mission and should be highly interesting to academic research and development testbeds. We are considering conducting a survey and comparison of Open5GCore with state-of-the-art open source toolkits in future publications, but this would go beyond the scope of the current article.

Fig. 2 FOKUS 5G Play-ground

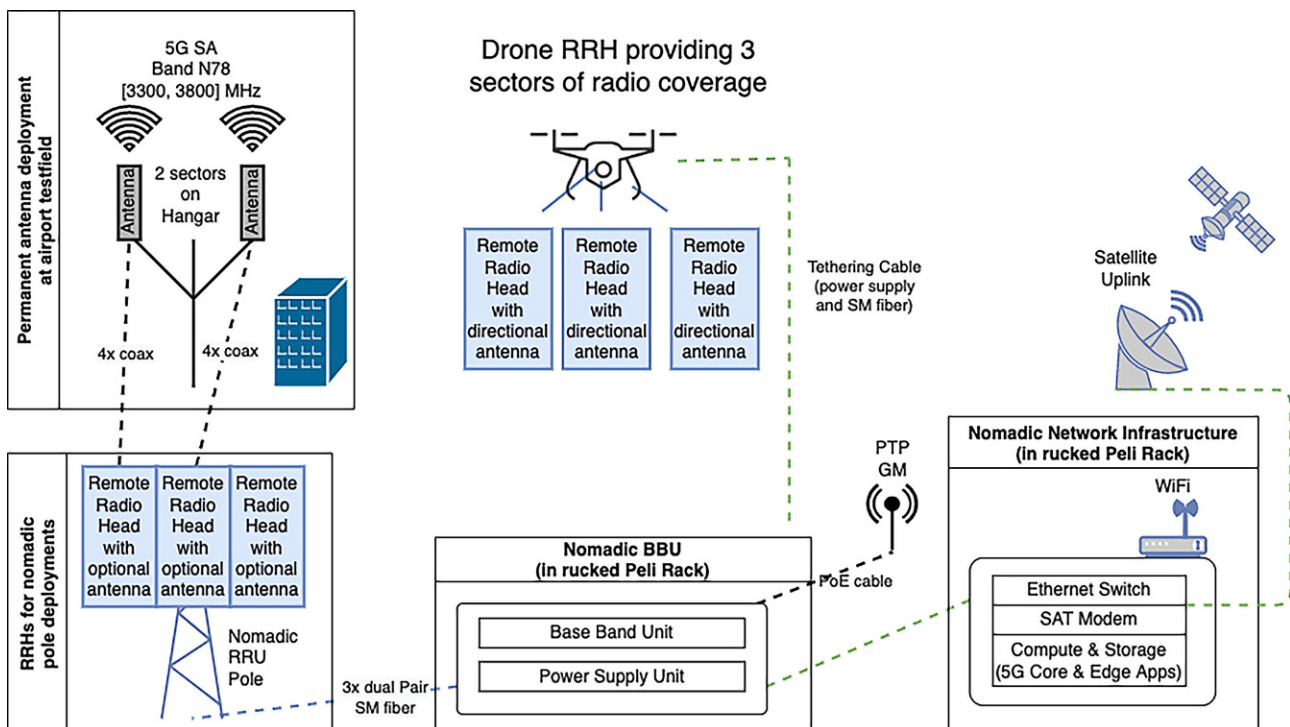
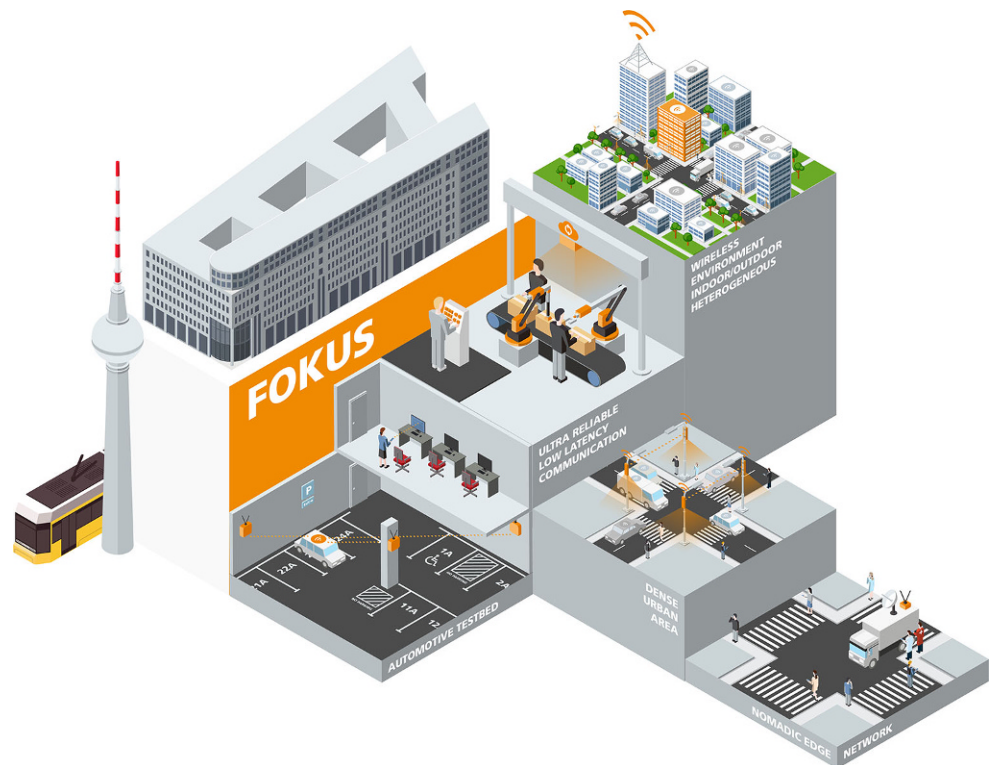


Fig. 3 Architectural components of the FOKUS 5G+ nomadic node

3.2 The Open 5G Playground

Based upon the Open5GCore, Fraunhofer FOKUS operates the Open 5G Playground: an open testbed designed to enable innovative product prototyping in a realistic, comprehensive 5G end-to-end environment, including calibration, benchmarking and interoperability tests between new prototypes and products [3].

The testbed provides heterogeneous radio access technologies in an indoor- and outdoor test field, including 5G stand-alone (SA) new radio (NR) from—amongst others—Huawei, Nokia, NodeB, as well as non-3GPP access technology including WiFi, mmWave, and visible light communication (LiFi). The 5G Playground provides outdoor coverage in the Berlin city center nearby Fraunhofer FOKUS as well as indoor coverage for the FOKUS' experimental 5G labs, and the underground parking deck (c.f. Fig. 2). With that, the testbed is well suited for various use case evaluations, ranging from IIoT applications, virtual and augmented reality, up to autonomous driving of automated guided vehicles (AGVs).

Operating in band n78, using the full 3700–3800 MHz channel allocated for campus networks in Germany, the architecture of the Open 5G Playground provides a validated blueprint for building industry-specific campus networks at other locations. With that, the FOKUS testbed becomes an essential part of key European experimental sites for 5G and beyond trials [39–42].

3.3 The FOKUS 5G+ Nomadic Node

In addition to the stationary testbed installation of the 5G Playground, the FOKUS Open5GCore is an essential component of the FOKUS 5G+ Nomadic Node. The Nomadic Node is a fully portable, autonomous nomadic 5G network for use case validations in the field and easy rapid testbed deployment on-site. “5G+” is denoting the flexibility to include any 5G beyond and 6G-ready RAN technologies, as well as emerging NTN technologies as backhauls. Its flexible architecture consists of four major functional blocks, providing namely network infrastructure with compute and storage, 5G base band unit, detached remote radio heads and external antenna systems, and backhauling towards the public Internet (e.g., via satellite backhauling). Fig. 3 illustrates one possible instantiation of a 5G+ Nomadic Node. It also captures the capability of the nomadic node to support various use cases, which require static deployment of antenna systems, portable telescope antenna poles, or even tethered drones carrying radio heads and antennae.

The implemented clustering of functional blocks allows for easily exchanging the attached base band unit and remote radio heads, which enables quickly transitioning from a traditional 5G commercial off-the-shelf (COTS) system into a novel Open RAN 5G deployment

making the 5G+ Nomadic Node an optimal portable platform for beyond 5G deployments.

3.4 Outlook—the future of Open Campus Networks

In this section we briefly outline the key drivers for the Campus Network evolution towards 6G.

3.4.1 Nomadic 5G networks

We have illustrated before, that there is a growing demand for nomadic networks. However, the deployment of nomadic, autonomous 5G networks, with variable time constraints at diverse locations, raises several challenges. First, frequencies used for the ad-hoc deployment will have to be allocated on-demand and potentially only for a short time. Schemes like dynamic frequency allocation or continuous spectrum trading need to reach maturity, to reliably enable use cases such as 5G networks for construction sites, or autonomous nomadic networks for first responders. In particular, the latter raises additional challenges: the unpredictable radio propagation characteristics of the target environment, which may be circumvented by supporting a variety of nomadic antenna systems ranging from traditional telescope antenna poll deployments up to tethered drones acting as flying base stations being close to the end users thus reducing radio attenuation. Especially drones yield to the research aspect of building 5G campus networks utilizing non-terrestrial network elements for hosting elements of the network core, radio units, or just acting as backhaul connectivity. Thus, nomadic 5G networks will evolve and merge with non-terrestrial network (NTN) architectures. All those aspects are addressed by ongoing lighthouse research projects of FOKUS [43, 44].

3.4.2 Getting ready for Open RAN

The decomposition of 5G RAN into the Open RAN split of radio units, decentralized software units, and centralized software units will bring significant flexibility in combining radio components of different vendors in a campus network. However, this openness is also given for the core and management and orchestration components and thus must be considered from an end-to-end perspective. End devices as well as RAN and core network functionalities can thus be combined dynamically and in line with the demand to form a modular and secure end to end 5G campus network. This orchestration, as well as management, operations and control can be combined with artificial intelligence and machine learning. The German BMWK project CampusOS [44] aims to provide validated system blueprints for several of those deployments, eventually building an Open RAN eco system for campus networks. The FOKUS 5G+ Nomadic Node is an integral part of the construction site use case in the latter project.

3.4.3 Evolution towards 6G

Nowadays, 6G is hyped and politically motivated to stipulate digital sovereignty for future telecommunication systems. From a technological perspective, future developments will rather be an evolution of 5G, which is also driven through innovations enabled by the flexible network architectures of 5G campus networks. Use cases driving 6G and the underlying technology, as looked at by current 6G light house projects, underline this [45–47].

As such, the 6G evolution will be driven by private campus networks; their geographically limited extension will make them a key candidate for utilizing micro-cellular infrastructures as provided by THz spectrum. Also, they will push and benefit from novel agile software architectures natively incorporating AI and ML for network optimization, operation, and even dynamic autonomous deployments [48, 49]. With that, campus networks drive the revolutionary evolution towards beyond 5G and 6G networks, and thereby push the sustainability and network resilience goals as recently outlined by the German government [7].

There is no doubt, that campus networks are considered internationally as innovation drivers for 5G towards 6G, as they provide a means to implement innovative features needed by different verticals. Many white papers published in the last 2–3 years, which use synonymous terms, like private/mobile/enterprise networks or non-public networks, provide evidence for this trend. It is worth looking at the major innovation spots addressed by 5G campus network research and development projects and to compare these with current 6G research topics as listed in Table 3. Note that this table is not aiming for completeness but meant only to highlight important trends.

Higher frequencies The drivers for higher frequencies are spectrum shortages in lower spectra around the globe and increased capacity requirements. When it comes to the 5G spectrum, we have witnessed the rise of mmWave [50] in recent years and current campus frequencies in 26 GHz are also becoming available in this context [12].

In 6G we can observe that (sub)terahertz spectrum is considered a key architectural driver and enabler

for new features, such as joint communications and sensing [51]. Another promising type of wireless communication is based on visible light spectrum. While promising high data rates, THz and visible light communication (VLC) are particularly promising for indoor and privacy aware controlled environments such as campus networks.

Joint communication and sensing The ability to combine telecommunications with sensing capabilities to simultaneously exchange information and observe the environment has seen increased interest in research towards future wireless networks. Localization and positioning, for example, are key capabilities in industrial 5G use cases and we can witness a high demand for appropriate solutions in automation and intra-logistics campus networks [52].

As mentioned above, 6G terahertz research is specifically going beyond positioning and extending towards utilizing the 6G RAN as a sensor. The resulting information can be collected and aggregated to create digital twins of networks and their environment, giving rise to new opportunities for management of radio resources and localization and positioning of end devices. Campus networks can make use of these added features for improvements in regards to surveillance and operational safety.

Softwarization Software-based network principles have been all around us for two decades and 5G is the first real global implementation of a softwarized mobile wireless network. The 3GPP SBA provided the opportunity for cloud-native and micro service type implementations of the core network architecture. In the future telecommunications networks like the 6G mobile network will have to further evolve this software-based approach to incorporate modern development techniques such as DevOps and CI/CD. The components of networks will be constantly updated, fixed and improved as vendors continuously develop them. This trend will require vendors and operators to embrace open source software and communities, as they play a key role in this environment.

Virtualization Network Function Virtualization (NFV) has been introduced with 3G and 4G already for IP Multimedia Subsystem (IMS) and Evolved Packet Core (EPC), driven by the exploitation of cloud computing principles. In addition to the rise of edge computing, in order to combine the cloud computing benefits with local requirements for privacy and low latency communications, NFV has become a key design principle for 5G [16] and also provides scalability and redundancy.

As virtualization technology has evolved in the recent years, so-called cloud native software design principles emerged. From virtual machines to containers and serverless computing as well as function as a service (FaaS), service design needs to con-

Table 3 Comparison of 5G campus networks research and potential 6G innovations

Research/innovation area	5G campus networks	6G continuum
Higher frequencies	mmWave	THz and Optical Wireless
JCAS/ISAC	Positioning	Positioning and Sensing
Softwarization	Cloud-native	Organic
Virtualization	Edge	Infrastructure free
Disaggregation	SBA, OpenRAN	Organic
Management	AI/ML optimizations	Holistic/scheduled network management
Rural Coverage	Direct-to-(GEO/MEO) Satellite	Multi-orbit/3D NTN

sider the virtualization of the infrastructure, to fully take advantage of it. Micro services are examples of the resulting architectures. The 6G network has to continue in this direction to reach the point of infrastructure-less networking. Particularly 6G campus networks should be able to operate in diverse deployment scenarios, which may include infrastructure-less segments or complete networks.

Disaggregation and aggregation Although we have already witnessed the disaggregation of the key core network functionalities in 3GPP Rel. 16 with the introduction of the SBA [19], it was mainly the rise of ORAN and the more generalized Open RAN concept three years ago, which sparked the global trend towards open and customizable 5G networks, in which operators of network infrastructures will have the freedom to choose their network components from different vendors and aggregate and particularly disaggregate their network functions in a plug and play mode. Obviously, this requires the proper identification of an appropriate functional split and corresponding industry wide standards for the interfaces identified [16, 53].

Whereas the Open RAN concept was invented by global network operators with the intent of lowering the costs of 4G/5G wide area networks through increased competition, nowadays the concept is considered key for building up economically highly customized campus networks and also to drive innovations in 5G [7, 44].

While it will probably take quite some time to establish an open network ecosystem based on Open RAN and to adopt these principles in existing networks, the concept in principle is guiding the way 6G architectures will look like. In particular we assume a higher degree of “RAN-Core” convergence in which former authentication, QoS and mobility management functionalities of the core network might be partially integrated as x/rApps in an Open RAN Radio Intelligent Controller (RIC), or functionalities of the Open RAN might be integrated in an extended core network architecture. Therefore, the 6G architecture is considered as a highly modular and agile system, which the authors refer to as “organic” [54].

Management The automation of network management has a long tradition, since the use of expert systems has been considered to assist the human operator some 30–40 years ago. The rise and corresponding hype around artificial intelligence (AI) and machine learning (ML) has led to the concept of zero touch management. In principle, AI/ML have traditionally been utilized for fault/performance/security management and network optimization. More recently, it has been considered to let them take an active part in network control, e.g., the real time RIC within Open RAN or the Network Data Analytics Function (NWDAF) within the SBA [19].

There is no doubt, that the operators of campus networks in particular, would benefit from these solutions, as they might lack the operational experience. But, we also have to acknowledge the additional reliability, availability, and resilience requirements of campus networks [55].

Early 6G architectures propose supporting AI/ML “by design”, thus representing integral ingredients of future 6G networks. The idea of AI native networks includes intelligence as a service as well as AI/ML based or assisted management and orchestration [56–58].

Universal access through NTN Universal access to mobile networks is considered an important societal value and a key design requirement for 6G. However, the deployment of 5G in areas outside the city centres and industrial hubs is not economical. Even the adoption of higher frequencies offers only limited coverage areas and the implied costs of building up the radio towers would be significant. NTN have emerged as a potential solution for remote access and backhaul of mobile networks. Therefore, the integration of satellite networks and 5G has been an international research topic for many years and the European Space Agency (esa) has launched a number of research projects which also stimulated corresponding 3GPP study items [59]. Thus, remotely located and even nomadic 5G campus networks can be connected with the greater Internet or enterprise networks. Lower, medium and geostationary orbit (LEO, MEO and GEO) Satellites and high-altitude platforms (HAPS) are being developed to provide direct network access to 5G devices [60]. These NTN technologies are considered a key pillar for the 6G architecture definition [61].

4 Conclusion

This article presented how the campus networks of 5G and beyond can inform, drive and accelerate the research and development effort towards ICT-2030 and 6G mobile wireless communication. Campus networks are a promising market with diverse use cases and requirements that will push 5G technology to its limits. Countries across the world have recognized their potential and started considering them explicitly within their radio frequency spectrum regulations. We have detailed how campus networks influence affects different aspects of wireless networks, such as frequency selection, management, infrastructure and disaggregation.

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References

- 5G Americas (2021) Private and enterprise networks. <https://www.5gamericas.org/private-and-enterprise-networks/>. Accessed 07.2022
- Fraunhofer FOKUS (2022) Open5GCore. <https://www.open5gcore.org>. Accessed 12 July 2022
- Fraunhofer FOKUS (2021) 5G Playground. https://www.fokus.fraunhofer.de/go/en/fokus_testbeds/5g_playground. Accessed 12 July 2022
- Fraunhofer FOKUS (2016) Netzinfrastrukturen für die Gigabitgesellschaft. https://www.fokus.fraunhofer.de/en/FOKUS/Gigabit_Studie. Accessed 2022-07-12
- TM Forum (2019) 5G, Evolution and Revolution. <https://inform.tmforum.org/research-reports/5g-evolution-revolution>. Accessed 2022-07-12
- Corici M, Emmelmann M, Hauswirth M, Magedanz T (2019) Paving the way for local and industrial 5G networks and testbeds. *Ercim news*, vol April 2019
- BMDV (2022) Gigabitstrategie der Bundesregierung. <https://www.bundesregierung.de/breg-de/aktuelles/gigabitstrategie-2017464>. Accessed 2022-07-12
- Grand View Research (2020) Private 5G network market size, share & trends analysis report by component (hardware, software, services), by frequency (sub-6 GHz, mmwave), by spectrum, by vertical, by region, and segment forecasts
- SNS Telecom & IT (2020) The private LTE & 5G network ecosystem: 2020–2030—Opportunities, challenges, strategies, industry verticals & forecasts
- IDTechEX Research (2020) 5G Technology, Market & Forecast 2020–202. <https://www.idtechex.com/de/research-report/5g-technology-market-and-forecasts-2020-2030/753>. Accessed 2022-07-12
- Federal Ministry for Economic Affairs and Climate Action (BmWK) (2020) Guidelines for 5G campus networks—Orientation for small and medium-sized businesses. Federal Ministry for Economic Affairs and Climate Action (BmWK), Berlin
- Bundesnetzagentur (2022) Regionale und lokale Netze. <https://www.bundesnetzagentur.de/DE/Fachthemen/Telekommunikation/Frequenzen/OeffentlicheNetze/LokaleNetze/lokalenetze-node.html>. Accessed 7 July 2022
- NOKIA (2022) Neutral hosts: A route to greater 5G profitability for CSPs? <https://www.nokia.com/networks/insights/neutral-hosts-path-to-5G-profitability/>. Accessed 2022-07-12
- Bhaskaran S Private 5G: What is it? How does it work?, 5G Technology World, 15 03 2022. <https://www.5gtechnologyworld.com/private-5g-what-is-it-how-does-it-work/>. Accessed 8 July 2022
- Fraunhofer Gesellschaft (2020) 5G Netze und Sicherheit. Fraunhofer Gesellschaft, Munich
- NGMN Alliance (2021) ODiN—operating disaggregated networks
- GSA (2021) 5G device ecosystem (Global mobile Suppliers Association)
- IEEE Advancing open-RAN: research, standards, and deployment (webinar). https://engagstandards.ieee.org/open-ran-webinar.html?utm_source=ieeesa&utm_medium=aem&utm_campaign=ct-2021&utm_content=open-ran. Accessed 2022-07-12
- 3GPP (2016) TS 23.501: 'System architecture for the 5G System; Stage 2'
- 3GPP (2017) TS 38.413: 5G NG-RAN, NG Application Protocol (NGAP)/Non-Access Stratum (NAS)
- 3GPP (2017) TS 24.501: Non-Access-Stratum (NAS) protocol for 5G System (5GS); stage 3
- 3GPP (2016) TS 29.244 interface between the control plane and the user plane nodes (3GPP)
- 3GPP (2015) TS 23.271 Functional stage 2 description of Location Services (LCS)
- Mavenir (2022) Converged packet core. <https://www.mavenir.com/portfolio/mavcore/converged-packet-core/>. Accessed 30 Aug 2022
- NEC (2022) 4G/5G converged core. https://www.nec.com/en/global/solutions/5g/4G_5G_Converged_Core.html. Accessed 30 Aug 2022
- IEEE ComSoc Rakuten Mobile, Inc. and NEC to jointly develop the containerized standalone (SA) 5G core network. <https://techblog.comsoc.org/2020/06/03/rakuten-mobile-inc-and-nec-to-jointly-develop-the-containerized-standalone-sa-5g-core-network/> (Created 3 June 2020). Accessed 30 Aug 2022
- Athonet (2022) Athonet 5G core. <https://athonet.com/products/athonet-5g-core/>. Accessed 30 Aug 2022
- Amazon (2022) AWS private 5G. <https://aws.amazon.com/private5g/>. Accessed 30 Aug 2022
- Google Announcing private network solutions on Google distributed cloud edge. <https://cloud.google.com/blog/products/networking/announcing-private-network-solutions-on-google-distributed-cloud-edge> (Created 14 June 2022). Accessed 30 Aug 2022
- Dano M Google starts selling private 5G. <https://www.lightreading.com/private-networks/google-starts-selling-private-5g/d/d-id/778238> (Created 14 June 2022). Accessed 30 Aug 2022
- IBM (2022) Edge computing solutions. <https://www.ibm.com/in-en/cloud/edge-computing>. Accessed 30 Aug 2022
- Microsoft Statement of compliance—Azure private 5G core preview. <https://docs.microsoft.com/en-gb/azure/private-5g-core/statement-of-compliance> (Created 29 June 2022). Accessed 30 Aug 2022
- Oracle (2021) 5G core network evolution. <https://www.oracle.com/industries/communications/service-providers-network/solutions/5g-next-generation-core/>. Accessed 30 Aug 2022
- De Souza Neto FJ, Amatucci E, Nassif NA, Farias PAM (2021) Analysis for Comparison of Framework for 5G Core Implementation. In: 2021 International Conference on Information Science and Communications Technologies (ICISCT)
- free5Gc (2022) Free5Gcor. <https://www.free5gc.org>. Accessed 30 Aug 2022
- Open Air Interfac (2022) 5G CORE NETWORK. <https://openairinterface.org/oai-5g-core-network-project/>. Accessed 30 Aug 2022

37. MAGMA (2022) A modern mobile core network solution. <https://magmacore.org>. Accessed 30 Aug 2022
38. Open5GS (2022) Open source project of 5GC and EPC (Release-16). <https://open5gs.org>. Accessed 30 Aug 2022
39. 5G-VINNI (2021) 5G verticals innovation infrastructure. <https://www.5g-vinni.eu>. Accessed 2022-07-12
40. 5GENESIS (2021) 5th generation end-to-end network, experimentation, system integration, and showcasing. <https://5genesis.eu>. Accessed 2022-07-12
41. 5G-VICTORI (2022) Vertical demos over common large scale field trials for rail, energy and media industries. <https://www.5g-victori-project.eu>. Accessed 2022-07-12
42. Koumaras H, Tsolkas D, Gardikis G, Gomez PM, Frascolla V, Triantafyllou D, Emmelmann M, Koumaras V, Osma MLG, Munaretto D, Atxutegi E, d. Puga JS, Aley O (2018) 5GENESIS: The genesis of a flexible 5G facility. In: 8 IEEE 23rd International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)
43. ALADIN (2022) Advanced low altitude data information system. <https://aladin-5g.de>. Accessed 2022-07-12
44. CampusOS (2022) Aufbau eines Ökosystems für Offene 5G-Campusnetze mit offenen Funktechnologien und interoperablen Komponenten. <https://campus-os.io>. Accessed 2022-07-12
45. Open6GHub (2022) 6G for society and sustainability. <https://www.open6ghub.de/en/>. Accessed 2022-07-12
46. 6G-RIC (2022) Open and secure 6G technologies as a global market opportunity for Germany. <https://6g-ric.de>. Accessed 2022-07-12
47. Bertin E, Crespi N, Magedanz T (eds) (2021) Shaping future 6G networks—Needs, impacts and technologies. IEEE Press/Wiley
48. 5GIA (2021) European vision for the 6G network ecosystem
49. Fraunhofer Gesellschaft (2021) On the road to 6G: Drivers, challenges, and enabling technologies. <https://cdn0.scrvt.com/fokus/6802ce7485f1a2e0/e5665a410eca/6g-sentinel-white-paper.pdf>. Accessed 2022-07-12
50. Rappaport TS, Sun S, Mayzus R, Zhao H, Azar Y, Wang K, Wong GN, Schulz JK, Samimi M, Gutierrez F (2013) Millimeter wave mobile communications for 5G cellular: it will work! IEEE Access 1:335–349
51. Rappaport TS, Xing Y, Kanhere O, Ju S, Madanayake A, Mandal S, Alkhateeb A, Trichopoulos GC (2019) Wireless communications and applications above 100 GHz: opportunities and challenges for 6G and beyond. IEEE Access 7:78729–78757
52. 5G-ACUA (2021) Position Paper—Our view on the evolution of 5G towards 6G. <https://5g-acia.org/whitepapers/our-view-on-the-evolution-of-5g-towards-6g/>. Accessed 2022-08-30
53. O-RAN Alliance (2022) Transforming radio access networks towards open, intelligent, virtualized and fully Interoperable RAN. <https://www.o-ran.org>. Accessed 30 Aug 2022
54. Corici M, Troudt E, Magedanz T (2022) An organic 6G core network architecture. In: 2022 25th Conference on Innovation in Clouds, Internet and Networks (ICIN)
55. Carrozzo G, Siddiqui MS, Betzler A, Bonnet J, Perez GM, Ramos A, Subramanya T (2020) AI-driven zero-touch operations, security and trust in multi-operator 5G networks: a conceptual architecture. In: 2020 European Conference on Networks and Communications (EuCNC)
56. Tataria H, Shafi M, Molisch AF, Dohler M, Sjöland H, Tufvesson F (2021) 6G wireless systems: Vision, requirements, challenges, insights, and opportunities. Proc IEEE 109(7):1166–1199
57. Uusitalo MA, Ericson M, Richerzhagen B, Soykan EU, Rugeland P, Fettweis G, Sabella D, Wikström G, Boldi M, Hamon M-H, Schotten HD, Ziegler V (2021) Hexa-X The European 6G flagship project. In: 2021 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)
58. Hexa-X (2021) D5.1 initial 6G architectural components and enablers
59. SATIS5 (2020) Demonstrator for satellite-terrestrial integration in the 5G Context, Eurescom. <https://satis5.eurescom.eu>. Accessed 30 Aug 2022
60. Starlink (2022) High-speed, low-latency broadband internet in remote and rural locations across the globe. <https://www.starlink.com>. Accessed 30 Aug 2022
61. Open6GHub (2022) Open6Ghub 6G for society and sustainability. <https://www.open6ghub.de/en/>. Accessed 30 Aug 2022

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