Telecommunication Systems (2023) 82:3–26
https://doi.org/10.1007/s11235-022-00978-z

Private 5G networks: a survey on enabling technologies, deployment models, use cases and research directions

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Accepted: 31 October 2022 / Published online: 20 November 2022

Abstract

Today's modern enterprises are adjusting to new realities of connectivity. As companies become more distributed and autonomous, emerging applications demand more bandwidth, low latency, more spectrum, and higher reliability. 5G technology can aid many industries or enterprises to make quicker and better business decisions. Private 5G networks, also called 5G Non-Public Networks (5G-NPN), is a 3GPP-based standalone 5G network positioned for a particular enterprise or use case that delivers dedicated network access. It sets to transform industry landscapes with networks capable of rapidly deploying modern use cases and the scalability to meet constantly increasing demands of data capacity and speed. They help generate more revenue for operators who can partner with enterprises to build and manage networks on-premise or in the cloud. The objective of this work is to offer a thorough summary of private 5G networks to assist academicians, researchers, and network developers to quickly grasp their functionalities without needing to go through the standards, specifications, or documentation. This paper discusses various key private 5G network design goals and requirements, examines its deployment scenarios, and explores spectrum considerations and security aspects. The paper presents several enterprise use cases to illuminate how the networks can deliver the demands and services expected by the industries. It also provides an overview of some of the open-source projects considered by various organizations for private network deployment. Finally, several research directions are introduced, emphasizing enterprise challenges to deploying 5G networks.

Keywords Private 5G networks · Spectrum · Industry 4.0 · Internet of things · Massive MIMO · Millimeter wave · Small cells

1 Introduction

Globally, the mobile data traffic approximately doubling up every year, the average smartphone usage exceeds 10 GB [1], the demand for high-speed internet connectivity increases every second and that's where 5G comes in. 5G technology provides the capability for high-speed connections, massive data growth, streaming, fast and uninterrupted sharing, and browsing for everyone. In 2019, the cellular phone carriers introduced the 5th generation wireless infrastructure standard for broadband wireless networks. It is future replacement to the 4G mobile networks that link most existing cell phones. 5G applications signify incredible opportunities for businesses, homes, consumers, and communities by delivering key functional drivers including Ultra-Reliable and Low-Latency Communication (URLLC), enhanced Mobile Broadband (eMBB), and Massive Machine-Type Communication (mMTC) [2]. 5G networks are driving the next generation of applications such as Industrial Internet of Things (IIoT), autonomous vehicles, Augmented Reality (AR) gaming, etc [3]. It supports use cases across a wide range of entities like manufacturing, utilities, agriculture, and municipalities helping organizations reduce costs, increase efficiencies, and improve customer experience.

The first 5G network design goal by ITU-R is the increased bandwidth with support for 20 and 10 Gb/s for download and upload speed respectively. The latency in the Radio Access Network (RAN) has been reduced to under 1ms to support very latency sensitive applications. [4,5] The network coverage has been improved in a cell to 10 Mb/s/m^2 with minimum

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date rate of 100 and 50 Mb/s for download and upload speed respectively [5]. The device density has been improved to a 1,000,000 devices per km2. The mobility has been improved and hence the coverage is reliable at speeds of up to 120 km/h and possible at up to 500 km/h [4,5]. All these enhancements in 5G allow for the creation of three new major service types, eMBB, URLLC and mMTC.

A private 5G network [6] is a standalone dedicated network for private use by an organization with different components as shown in Fig. 1. As a critical component of digital transformation, private 5G delivers the same technology benefits as public 5G but gives you more control over your network including the policies, security, services, and data. It also offers more flexibility than traditional 5G networks such as better coverage options for remote applications, fewer technical challenges for large indoor spaces, and access to more shared spectrum. As demand from mission-critical businesses drives initial investment, International Data Corporation (IDC) forecasts that the worldwide private 5G network infrastructure market to achieve $5.7 billion in 2024 [7]. According to a survey, the private 5G network market size is projected to attain $14.28 billion by 2028, reaching a Compound Annual Growth Rate (CAGR) of 39.7% between 2021 and 2028 [8].

This survey paper on private 5G networks is structured as follows: Sect. 2 presents an introduction to private 5G networks. Section 3 discusses the requirements and key enablers for private 5G networks with respect to enterprises to realize the best of benefits of 5G. Sections 4 and 5 discusses the deployment and enabling technologies for the private networks and different spectrum considerations available currently. A comparison overview of 5G vs Wi-Fi 6 wireless technologies and network slicing vs private 5G networks are discussed in Sects. 6 and 7 respectively. Next two sections present the private 5G networks related use cases for industrial transformation. Section 11 explores the security aspects of enterprise concerns that address a reliable and secure private network. The last section provides a research recommendation for private networks followed by conclusion.

2 Private 5G networks

Digital transformation is accelerating the need for advanced network technology that enterprises want to take benefit of the high performance and low latency of 5G networks [9]. Business critical data and network access must be secured and not impacted by outages in public networks. This need is driving the rise of private networks. A private network gives a means to share data securely and autonomously and it never touches the public internet [6]. The companies connect to this, members only network more access points are available for a company to share information easily and securely. As a result, private network deployments are growing exponentially, and they unleash the power of the network to deliver secure, reliable, and scalable solutions [10]. Enterprises also have added control over private than public networks including service levels, data access, residency, and security. Technologies like ethernet, Wi-Fi and more recently LTE are widely deployed as private network technology solutions and now 5G has been added to that mix now with respect to a private 5G network in the terminology of the 3GPP which is called a Non-Public Network (NPN) [11]. So, the public network would be the network that typical subscribers would be using, and they would have a subscription to a Mobile Service Provider (MSP).

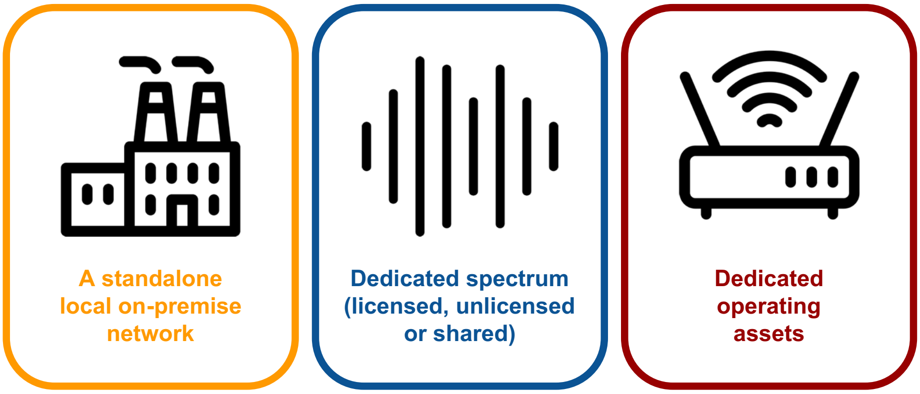
Private 5G networks (also called NPNs), represent a virtual or physical cellular systems installed for private use by governments, enterprises, and other institutions. They comprise coverage areas of any size, from indoor or outdoor, small to wide, by mixing and matching different types of radios. It suits all enterprise or business site types and traffic circumstances, even as their networks grow in complexity and scale. Private 5G networks or NPNs can be deployed both in entirely private mode (i.e., on-premises) and in hybrid mode (i.e., integrated with MSP network) to permit MSPs to control their current network and spectrum assets [12]. It controls localized small cells, micro towers, and Multi-access Edge Computing (MEC) to deliver 5G network coverage and connectivity, like a scaled-down version of a public cellular network. This is illustrated in the Fig. 2. It delivers critical voice, data, and video communication in the form of Push to Talk (PTT) and Voice over LTE (VoLTE). The private 5G network solution employ 5G cellular technology and 4G LTE and lets the MSP to deploy an exclusive private network subscription for their marketplaces based on their network features and enterprise strategy. The key enabling specifications of 5G networks, such as high network availability, ultra-low latency, large volume data aggregation and high device density capabilities, merge seamlessly with the growing requirements of Industry 4.0 [13].

3 Potential requirements and enablers of private 5G networks

3.1 Requirements of private 5G networks

Networking and telecommunications giant Ericsson define 5 key requirements for private 5G networks. Industries are digitalizing their processes and modernizing their private networks. The networks need to be resilient, secure, high performing and future proof for enabling business-critical and mission critical operations [14]. A private 5G network should have full control of coverage, users, devices, Quality

Fig. 1 Components of a Private 5G Network



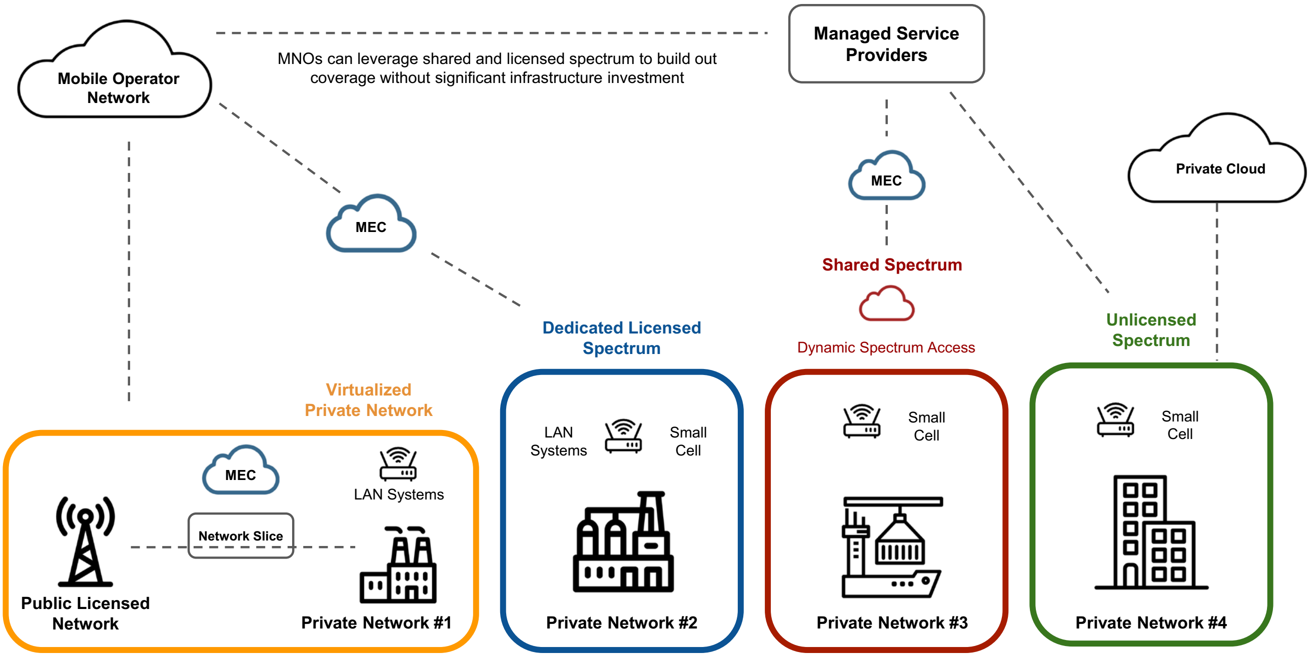


Fig. 2 Private 5G Network Architecture

of Service (QoS), improved security, flexible deployments for all situations [10]. The main business and mission critical capability requirements are illustrated in the Table 1.

3.2 Key enablers of private 5G networks

5G technology as a private 5G network is an exciting suggestion with benefits of 5G such as latency of sub 1 ms, reliability exceeding 99.999% and high data transmission rates in the range of Gbps [15]. The latest 3GPP's 5G global standard outperforms Wi-Fi and 4G LTE but also offers advantages beyond [2]. For example, the connection density of devices has enhanced tenfold over 4G LTE, making 5G attractive and potential for Massive IoT deployments. Therefore, 5G is ideal for private network deployments with high numbers of end devices for industry, healthcare, and other enterprises. Besides, 5G can support for network slicing to make network operation and control easier for the private network operator. Private 5G networks have novel features (as listed in Table 2) that condense into direct profits for the digital enterprises [16].

4 Deployment and enabling technologies

Private 5G mobile networks is a 5G system personalized for specific enterprise or industrial use cases like Healthcare, Industrial Internet of Things (IIoT), where definite requirements like latency, security, QoS, etc. play an important role. With the use of current mobile radio systems like 5G or LTE, private networks are built for dedicated resident applications such as a factory, hospital, airport, or agriculture field. The implementations of private networks based on the LTE system [17] and initial deployments of 5G technology [18] are

Table 1 Requirements for private 5G networks

Requirements	Description
Reliability	Must provide Ultra Reliable Low Latency Communication (URLLC), capacity, adequate network coverage, and robust handover functionality to improve reliability in transmitting data traffic in terms of fixed duration, volume, and the probability of success
High availability	Must promise maximum availability to the end user through robust solutions. Downtime can be zero by constructing redundant critical elements and control system maintenance
Security	Must allow complete end-to-end security and privacy for infrastructure, data, and personnel from threats. Should comply with the security principles of CIA triad, namely, confidentiality, integrity, and availability
Interworking/interoperability	Integration with public 5G networks to ensure service continuity for mission-critical applications (autonomous vehicles) that may require to hop networks from a private to public network

Table 2 Key enablers of private 5G networks

Drivers	Description
Guaranteed coverage	Usage in remote and underserved areas, indoor/in-building, seamless mobility
Network control	Control over resources, operations, and network management
Performance	Profiles that will support demanding applications and QoS guarantees
End user data protection traffic prioritization	Identity and Access Management (IAM), privacy and data integrity prioritize applications based on the traffic, isolate traffic based on business and technical needs
Customization	Ensure the enterprise meets its business needs
Ultra-low latency	Sub 1 ms latency

already existing. Private 5G networks are intended for business markets and will deliver a transformation in the method of providing mobile services. The customers and recipients are an industry or enterprise which are associated with a specific applications, requirements, and location. Privacy is an important feature of these networks where communication ends within the institution or enterprise and do not depend on the involvement of operator's public mobile network. For example, the enterprise implements the infrastructure and a Mobile Network Operator (MNO) with a spectrum license leases the band to the enterprise. The enterprise uses the resulting private network to provide service.

4.1 Deployment models

The implementation of a dedicated private 5G network for an enterprise can be done using several options. It can be owned by an enterprise itself or managed by an MNO, and can utilize licensed, unlicensed with schemes like New Radio Unlicensed (NR-U), Licensed-Assisted Access (LAA), or License-shared using schemes like Citizens Broadband Radio Service (CBRS) spectrum, and Licensed Shared Access (LSA) [19]. The various high-level private 5G network deployment choices are illustrated in the upcoming section. As demonstrated in Fig. 3, they can range from entirely standalone, combined with the public network of an MNO, network slicing specific to 5G up to Radio Access Network (RAN) sharing [10]. In the later section of the paper, the importance of network slicing [20] is discussed. The deployment choice with respect to an enterprise is decided based on the following characteristics:

- Spectrum owner and management (Transport/radio/core network)-MNO/enterprise/third party/venue owner.
- Licensed or unlicensed or shared spectrum.
- Capability/QoS requirements or any other dedicated resources.
- Single premise or Multiple premises.

4.2 3GPP characteristics for private 5G

The features defined by 3GPP [19] to enable the private 5G networks is illustrated in the Fig. 4. These features consent the

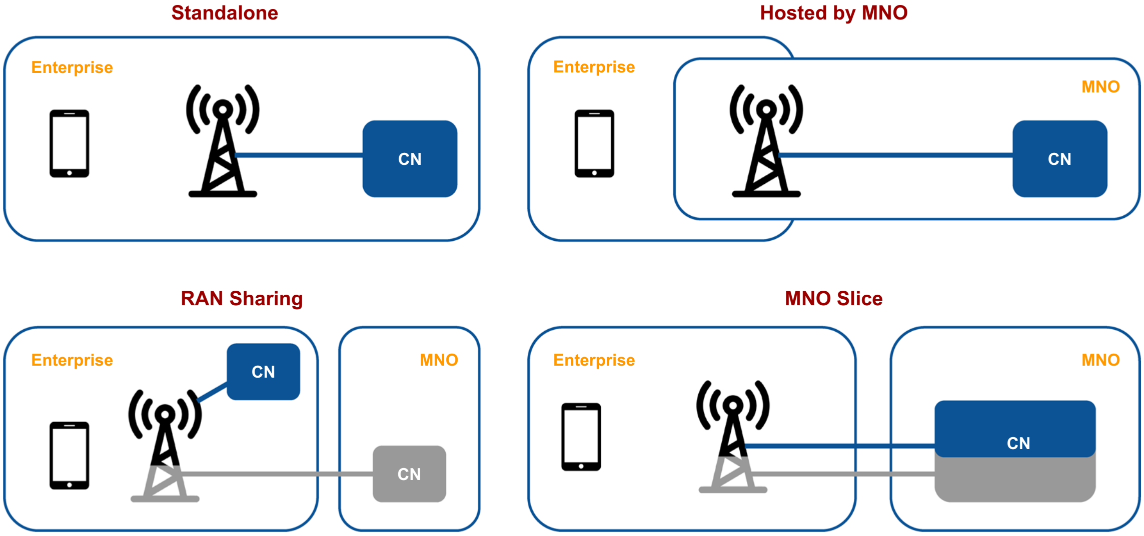


Fig. 3 Private 5G networks deployment options

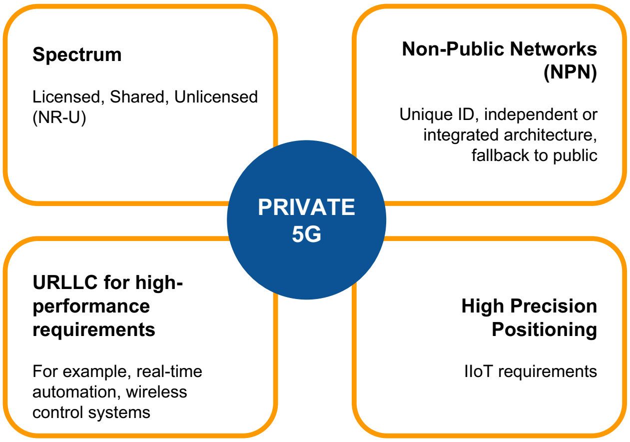


Fig. 4 3GPP characteristics for private 5G networks

private 5G to be considered as a good substitute to Wi-Fi 6 or wired solutions in the private/vertical sector. 5G technology being 3GPP defined, scalable, flexible, and future-proof, with high-performing radio, augmented for local services. The following aspects are suitable of private 5G networks.

- Security features and well-defined mobility which suit specific requirements for a given application (e.g., industry automation).
- Features such as the software-based core, centralized management, Control Plane (CP) - User Plane (UP) split, virtualization, Self-Organizing Networks (SON) allows it to stand out.
- Flexibility by spectrum access methods, high performance characteristics defined for URLLC class. For IIoT requirements, private 5G will offer high precision positioning [21].

4.3 5G Non-public network (NPN)

5G technology provides another feature called a Non-Public Network (NPN), i.e., the 3GPP defined name for a private 5G network. It allows deployment of dedicated 5G network for private use. From 3GPP's perspective, there are two deployment versions of NPN exists, namely, Standalone NPN (SNPN) and Public Network Integrated NPN (PNI-NPN) [22] as illustrated in Fig. 5. The difference between them is discussed in Table 3.

4.4 Private 5G deployment options

The architectural aspects of private 5G networks are introduced by 3GPP. As discussed in previous section, Private 5G networks can be deployed in two ways, viz., an independent private network (SNPN) and integrated private network (PNI-NPN). In the first option, a physically isolated 5G island (private 5G network) is deployed without the involvement of network operator. This 5G island can be constructed by enterprise themselves or by an operator. The latter is deployed by sharing the MNO's public network supplies across enterprises using approaches such as RAN sharing, RAN and Control Plane sharing, RAN and core sharing, network slicing etc. In this option, the MNOs will construct the private 5G networks for enterprises. The different types of extended deployment options are listed below and illustrated in the Fig. 6.

- Independent private 5G LAN by enterprise (full private, local 5G frequency, no sharing).
- Independent private 5G LAN by MNO (full private, licensed Frequency, no sharing).

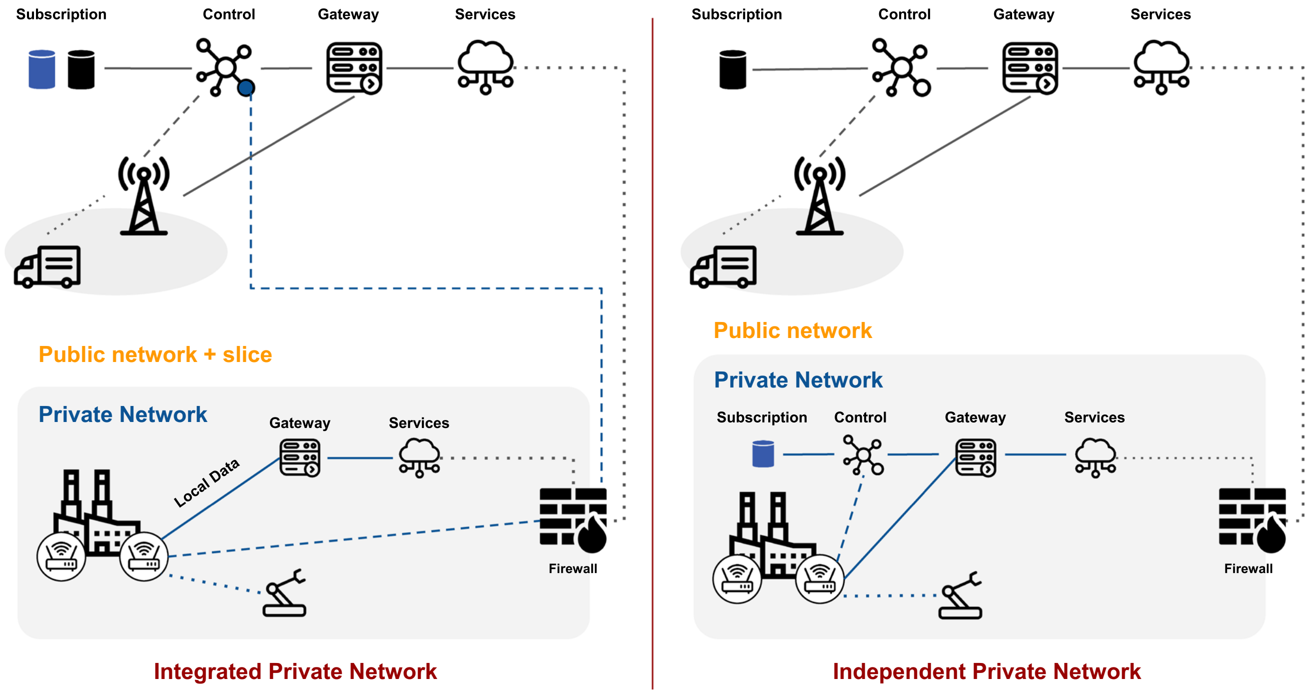


Fig. 5 Integrated vs Independent Private 5G Networks

Table 3 Standalone NPN Vs public network integrated NPN

Features	Standalone NPN (SNPN)	Public network integrated NPN (PNI-NPN)
Type	Individual	Integrated
Deployment and operation	Deployed and operated by an NPN operator, hence no interaction with an MNO/SP (service provider).	Deployed with the support of an MNO/SP
Spectrum	Own, unlicensed, shared	MNO spectrum, unlicensed, shared
Devices/SIMs/Subscriptions	Own responsibility (One or more NPN subscriptions per User Equipment (UE))	Different approaches such as RAN sharing, RAN and core sharing (based on dedicated spectrum, network slicing, etc.)
Roaming	No roaming	Standard roaming
Investment	High Capex & Low Opex	Low Capex & High Opex
Security	Own responsibility	End-to-end security provided by MNO

- RAN and signalling shared.
- Network slicing (RAN and core sharing).
- RAN and control plane sharing.

Independent private 5G LAN by enterprise Private network deployed by enterprise (includes UDM, 5G Core CP, UPF, gNB) within its premises (building) and entirely isolated from the MNO's public network [19]. The frequency employed is local 5G frequency and not MNO's licensed frequency. The subscription and user information will be stored locally by the enterprises. The enterprise also handles the control of the network and data services, and hence the network functions on a dedicated spectrum.

Independent private 5G LAN by MNO This network architecture is like that of previous model. The only difference is the 5G LAN in the enterprise is built and operated by an MNO with their individual licensed 5G frequency spectrum.

RAN and signaling shared Here, UDM, 5G Core CP and UPF are installed within the enterprise and hence the network services are handled locally [22]. 5G Next generation Base stations (gNB) and the spectrum are shared between the public and private network (called RAN sharing). MNO will handle the network and user control. Private network (private slice) and public network traffic are distributed to private UPF in the enterprise and UPF in the MNO's edge cloud respectively.

Network slicing (RAN and core sharing) In this option [23], UDM, CP and UPF are deployed in the MNO's edge cloud and only gNB is implemented inside the enterprise. Private and public network share "logically detached 5G Core

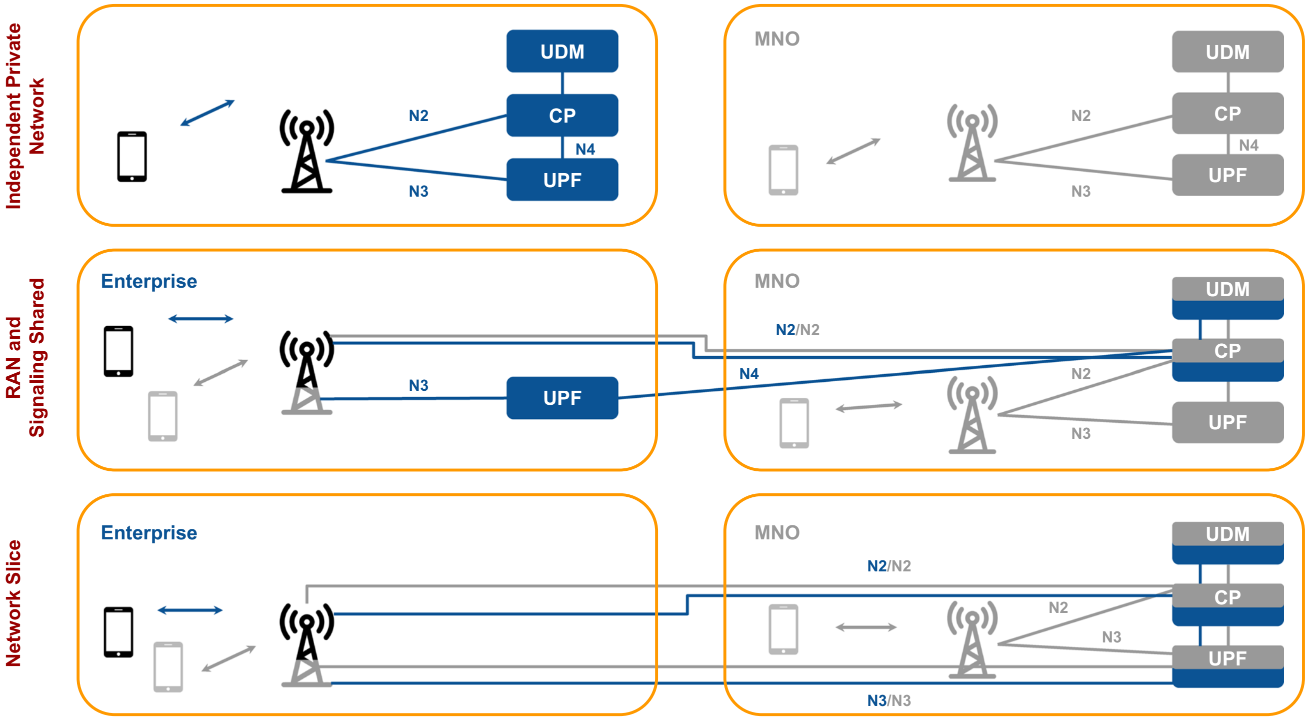


Fig. 6 Extended deployment choices for private 5G networks

and RAN" (UDM, UPF, 5G Core CP and gNB). This concept is used to understand a virtual network for a definite application is logically disconnected from other virtual networks called End-to-End (E2E) Network Slicing.

RAN and control plane sharing Inside the enterprise, there are dedicated UPF and gNBs built in. UDM and 5G Core CP maintained at MNO's edge cloud are shared between public and private networks [22]. The UDM, 5G Core CP and gNB are logically divided and the UPF is physically separated. Private network (private slice) and public network traffic are delivered to private UPF in the enterprise and UPF in the MNO's edge cloud respectively. The investigation of pros and cons of the most important deployment options are illustrated in the Table 4.

4.5 Private 5G deployment challenges

The demand for network bandwidth is increasing rapidly. According to Cisco's report [24], mobile data traffic is anticipated to reach a rate of 930 exabytes per year by 2022. In 2017, the average traffic per mobile user per month was about 2.3 GB, and it's estimated to be around 13.3 GB per month by 2022. To solve this problem, a new era of 5G has commenced and MNOs are accelerating 5G network deployment. Globally, private 5G networks are a relatively new technology and real-life deployments are out there. However, the challenges related to spectrum usage, cost, lack of knowledge are potentially going to be limiting factors. In this section, the key limitations or challenges associated with the private 5G deployment are discussed.

Regulatory challenges More RF spectrum is essential for 5G networks, and it is not an easily accessible resource. Most of it depends on 'licensed spectrum'. The complete range of effective spectrum usage need to be addressed [25]. With invent of 5G NR-U, unlicensed spectrum, the deployment of private 5G networks will become easy for enterprises to manage.

Technical challenges The higher frequency range (5 GHz and higher) adoption leads to higher data transmission rates. This higher data rates could bring overall network latency to 1 millisecond (theoretical) for 5G networks. The coverage range of these higher frequencies are much smaller which is another major challenge. Increase in cell tower count will solve the challenge.

Integration challenges The integration between spectrum assets, technological components, requirements, use case, applications, and nomenclature is one other major challenge. Private 5G mobile network integrators are required to build a case-specific network.

Lack of skilled network professionals MNOs have planned to rollout 5G as fast as possible and hence this would require skilled network engineers to implement this new age technology. Most enterprises don't have skilled professionals in their current workforce and search for talented personnel or train the current workforce.

Table 4 Private 5G network options

Deployment models	Pros	Cons
Independent Private 5G LAN by enterprise	• Privacy and security: data traffic, subscription and operation information, etc.	• High Capex for deployment
	• Autonomous QoS assurance	• Need for skilled operational personnel (Enterprises should own skilled engineers)
	• Ultra-low latency (all components nearby)	• High spectrum/licence cost
	• No subscription charges for users	
RAN and signaling shared	• Lower Capex	• Subscription information stored at MNO
	• Privacy and security: data traffic	• Need for skilled staff (troubleshooting)
	• Ultra-low latency	• Subscription charges for users
	• Licenced spectrum from MNO	• Dependency on MNO's network for signalling
Network Slicing (RAN and Core sharing)	• Logical isolation from the public network	• Dependency on MNO for QoS and no physical separation
	• Lower Capex	• Higher latency
	• Licenced spectrum from MNO	• Subscription information stored at MNO
	• SLA maintained for network by MNO	• Subscription charges for users

Government regulatory standards and policies Due to government regulations and policies, 5G deployment will happen at a varied pace with certain mixed and common features across different countries. This signifies that every country and/or continent have their own set of regulatory standards and norms, even though the technical parameters are quite common. This incremental nature of 5G deployment poses another significant deployment challenge. MNOs need to comply with the government regulatory standards established for delivering 5G mobile network services to the customers.

5 Spectrum considerations

Most wireless network systems depend on radio waves that can transmit signals back and forth between customer's devices and a mobile network service provider. To run these systems, firms like Sprint or Vodafone must buy space in the radio frequency spectrum. Frequency (number of cycles per second) for 5G is measured in hertz (Hz) and stated in kilohertz (kHz, which is 1000 Hz), megahertz (MHz, 1 million Hz), or gigahertz (GHz, 1 billion Hz). Radio Frequency varies from 3 kHz to a maximum of 3000 GHz. The radio frequency spectrum is normally divided into three groupings: high-band (between 24 and 100 GHz), low-band (below 1 GHz) and mid-band (between 1 and 7 GHz). Most countries consider spectrum as a natural resource and their usage is measured by respective national authorities which distribute resources according to the country's requirements. Traditionally, the wireless industry focused on licensed spectrum but there are three categories of spectrum (as shown in the Fig. 7, licensed spectrum, shared spectrum, and unlicensed spectrum in 5G [26–29]. Unlicensed spectrum is an important one and it can be used by anyone, anytime. This section of the paper outlines the key private 5G spectrum positions, which focus on the areas where regulators, governments, and the mobile industry must cooperate to realize high-performance private 5G networks.

5.1 Shared spectrum for 5G networks

The worldwide allocation of 5G spectrum covers a wide range from 410 to 52,600 MHz [26]. The spectrum's high-end falls in the millimeter range, which is unique to 5G technology. It typically enables ultra-low-latency and high-throughput for applications based on its high bandwidth. Private 5G networks need and utilize spectrum across a range of frequencies, subject to different license terms. Enterprises manages their network in licensed spectrum and requires a license from a license holder, usually an MNO) or from the national regulator. This model based on licensed spectrum will persist in private 5G networks. However, a scale of new spectrum choices is budding that will facilitate the private network implementation level rapidly. The global snapshot of allocated 5G spectrum [27] which includes the different spectrum, spectrum range for private 5G networks and their status as of December 2020 is illustrated in the Table 5.

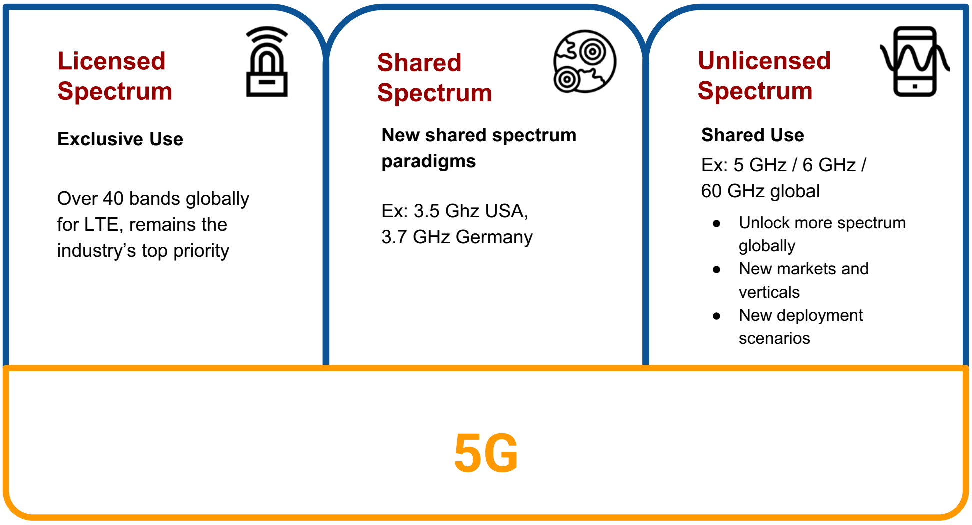


Fig. 7 5G Spectrum types

Table 5 Snapshot of allocated 5G spectrum

Country	5G Spectrum allotment	Private 5G Spectrum range	Availability [27,28]
Global	NR-U (unlicensed)—license assisted and standalone	5 GHz	Available
USA	NSA Sub-6 GHz, mmWave, Sub-6 FDD, standalone	5.9–7.1 GHz	Available
India	NSA Sub-6 GHz, mmWave, standalone	5.2–5.5; 5.7–5.9 GHz	Approved; available 2022 and beyond
Japan	NSA Sub-6 GHz, mmWave, Sub-6 FDD, standalone	5.2–5.7 GHz	Available
China	NSA Sub-6 GHz, Sub-6 FDD	5.2–5.3; 5.7–5.8 GHz	Available
Europe	NSA Sub-6 GHz, Sub-6 FDD, mmWave, standalone	5.9–6.4 GHz	Approved; under study/review
Australia	NSA Sub-6 GHz, Sub-6 FDD, standalone	5.2–5.8 GHz	Approved; available 2021 and beyond
Korea	NSA Sub-6 GHz, mmWave, standalone	5.9–7.1 GHz	Approved; under study/review
Latin America	NSA Sub-6 GHz, Sub-6 FDD, standalone	5.2–5.8 GHz	Approved; available 2021 and beyond

5.2 5G NR-unlicensed spectrum

5G New Radio Unlicensed (NR-U) is a new standard and major milestone to realize its foresight for high-performance 5G mobile networking in unlicensed spectrum [28] and eliminates the dependency on licensed MNOs. It can deliver higher data speeds, more reliability, ultra-low latency, increased availability, and massive network capacity. NR-U can help develop private networks with the power of 5G and lighten the spectrum constraints to deliver high-performance 5G experiences. In 5G NR Release 16 specifications [29], 5G NR-U is defined as the primary global cellular standard with both standalone and anchored use of unlicensed spectrum. This specification allows mobile devices to access up to 400 MHz (as shown in the Fig. 8) of unlicensed bandwidth in the downlink and 100 MHz of unlicensed spectrum bandwidth in the upload link. 3GPP Release 16 [30] starts with 5G NR-U in the 5 GHz unlicensed band. The 5G NR-U standard is pitching up to support the new unlicensed 6 GHz greenfield spectrum, tailed by the 60 GHz millimeter wave spectrum band which is developed as part of Release 17. 6 GHz unlicensed spectrum band brings new bandwidth for 5G and Wi-Fi and flexible ways to be used in outdoor and indoor environments. The chart of prospective 6 GHz unlicensed spectrum for 3GPP release is represented in Figure. With standalone NR-U, the private 5G networks can be deployed easily. This standalone NR-U has been designed and intended to collaborate with other unlicensed technologies such as Wi-Fi and extend simple installation procedures that Wi-Fi is valued [30]. It empowers support of mobility offload and neutral host networks use cases. With these benefits, the standalone NR-U incorporates the ability of high-performance 5G to private networks for enterprises without demanding any licensed spectrum.

6 Private 5G networks vs Wi-Fi 6

In this section, we explore the technical and implementation aspects of different technologies such as Wi-Fi 6, public and private 5G networks. Wi-Fi 6 and 5G are the next generation major stacks available to us for access into the internet network [31,32]. These technologies are very complementary and decide the amount of bandwidth you receive, the con-

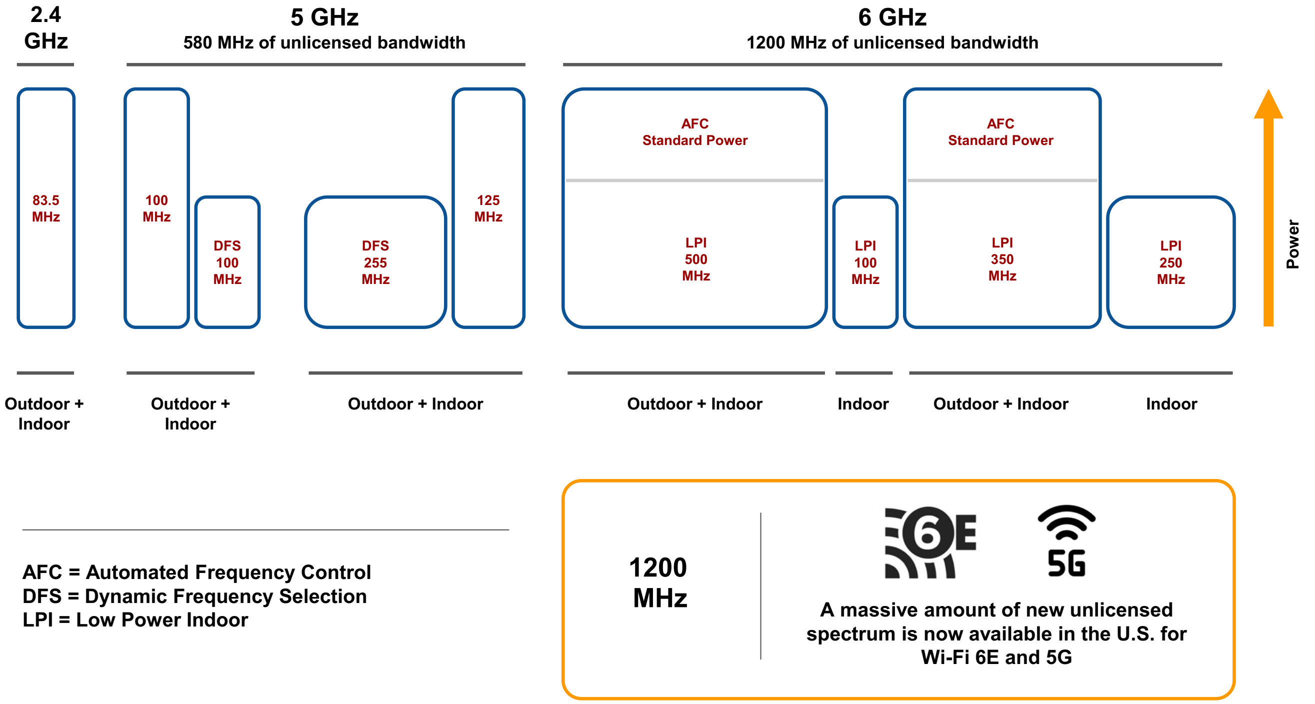


Fig. 8 5G NR-unlicensed spectrum consideration

sistency of the bandwidth and how reliable the connection is. Wi-Fi 6 (also called IEEE 802.11ax) is the next generation enhanced Wi-Fi standard [31] which is one of the most advanced technologies that meets today's demands for digital transformation. Compared with private cellular networks, Wi-Fi deployment is faster, easier, and cheaper [32]. Wi-Fi 6 can deliver all the promises that 5G makes including ultra-low latency, multi gigabit connectivity and high connection density. 5G is largely for outdoors and pervasive as a cellular today [34]. For indoors or inside a building, Wi-Fi will have great coverage and Wi-Fi 6 will dominate. It's more seamless since the work on the handoffs between these two is a significant characteristic. With more cell towers beaming out 5G and Wi-Fi 6 enabled routers getting added, the internet speed at home and on the go will become much faster with lower latency. Table 6 provides the comparison of various features of wireless access technologies such as 5G, Wi-Fi 6 and private 5G networks which includes frequency coverage, speed, latency and much more [31–35].

7 Network slicing and private 5G

MNOs are driven to start deploying network slicing solutions now to tap into the business-to-business opportunities created by 5G [36–40]. A key success factor is the ability to quickly answer customer needs in an economical way. However, the complexity of managing many slices and customers threatens the whole 5G business model. Automating the entire lifecycle management of a core network slice enables you to overcome that challenge. Network slicing considers taking one physical network end-to-end and dicing it up into virtual network slices with each slice being able to be controlled independently [37]. Each slice may have dedicated resources (core, access, and transport) that are not used in other slices and therefore they can be optimized to meet diverse performance requirements that are part of 5G ecosystem [38]. These network slices are an end-to-end concept required by customers for their multiple end-to-end individuals, independent, logical networks [39–41]. Each of these networks are called network slices and an operator can create several numbers of slices such as RAN, core and transport slices. Each individual domain has a controller, RAN controller, core controller, transport controller, and an end-to-end orchestrator.

There are three usage scenarios developed by the International Telecommunications Union (ITU) and have subsequently been adopted by 3rd Generation Partnership Project (3GPP) as three standardized network slices [37]. Private 5G networks will produce set of network slices for each of these usage scenarios as exhibited in the Fig. 9. The first one called enhanced Mobile Broadband (eMBB) is intended to provide the types of services that would typically use 4G for web browsing, video streaming, the type of traffic for email applications and the applications that often requires very high peak data rates [37,38]. Maybe is not too sensitive to latency, but very bursty in nature. The second category of

Table 6 Summary of features of private 5G networks and Wi-Fi 6

Features	5G	Private 5G	Wi-Fi 6 (802.11ax)
Data rate	Up to 10 Gbps	Up to 1 Gbps Maximum speed of 9.6 Gbps	
Frequency Ranges	• Licensed, unlicensed spectrum.	• Licensed, lightly licensed, unlicensed, or shared spectrum.	• Unlicensed spectrum
	• Low bands (for blanket coverage) 1 GHz	• NR-Unlicensed spectrum (5–6 GHz and above) as per 3GPP	• 2.4 and 5 GHz, extending to 1 and 6 GHz
	• Mid bands (coverage and capacity) 1–6 GHz		
	• High bands/millimetre wave (mmWave) for super fast speed over short distances—above 24 GHz		
Latency and Reliability	• Ultra-Reliable Low-Latency Communication (URLLC)	40–50 ms, when maintained privately	100 ms, as load increases, can't guarantee high reliability or low latency
	• 99.9999% reliability (six nines)		
Mobility	Roaming from private to public networks, handover at high speed (500 km/h relative)	Roaming from public to private networks, handover at high speed (350 km/h relative)	Fixed locations
Interference	Licensed, unlicensed and no interference	Licensed, unlicensed and no interference	Unlicensed, interference may occur
Density	1 million devices per square kilometer (km^2)	1 hundred thousand devices per square kilometer	4× improvement in dense environment (1000 per Access Point)
Coverage Scenario	Outdoor WAN	Enterprise campus	Indoor super high density
Virtualization	Network slicing (serving multiple types of networks IIOT, Data, Video, etc.)		Passpoint (multiple public networks on same infrastructure)
Battery life	mMTC targets up to 10 years or longer battery life of sensors	up to 10 years battery life of sensors	Suited for mobile phones
Environment	• Working remotely	• Factory	• Office environments
	• Driving	• Smart building	• Shopping mall
	• Commercial street	• Construction	• E-classroom
	• Community	• Hospital	• Hospital
Deployment period	Long (WAN: 1–1.5 years)	Medium (LAN: 3–6 months)	Less (days to months)
Network security	Security edge protection proxy (SEPP), security anchor function (SEAF)	Security anchor function (SEAF), subscription permanent identifier	Wi-Fi protected access (WPA3)
Security	High	Very high	Weak (WPA 2/3 vulnerable to hacking)
Availability	Commercial availability from 2020	Available	Wi-Fi 6E certified
Use case examples	• Mobile backhauls	• Industry 4.0	• UHD video streaming
	• Autonomous vehicle	• Mining	• Mobile AR/VR
	• Fixed wireless access	• Healthcare	• High speed tethering

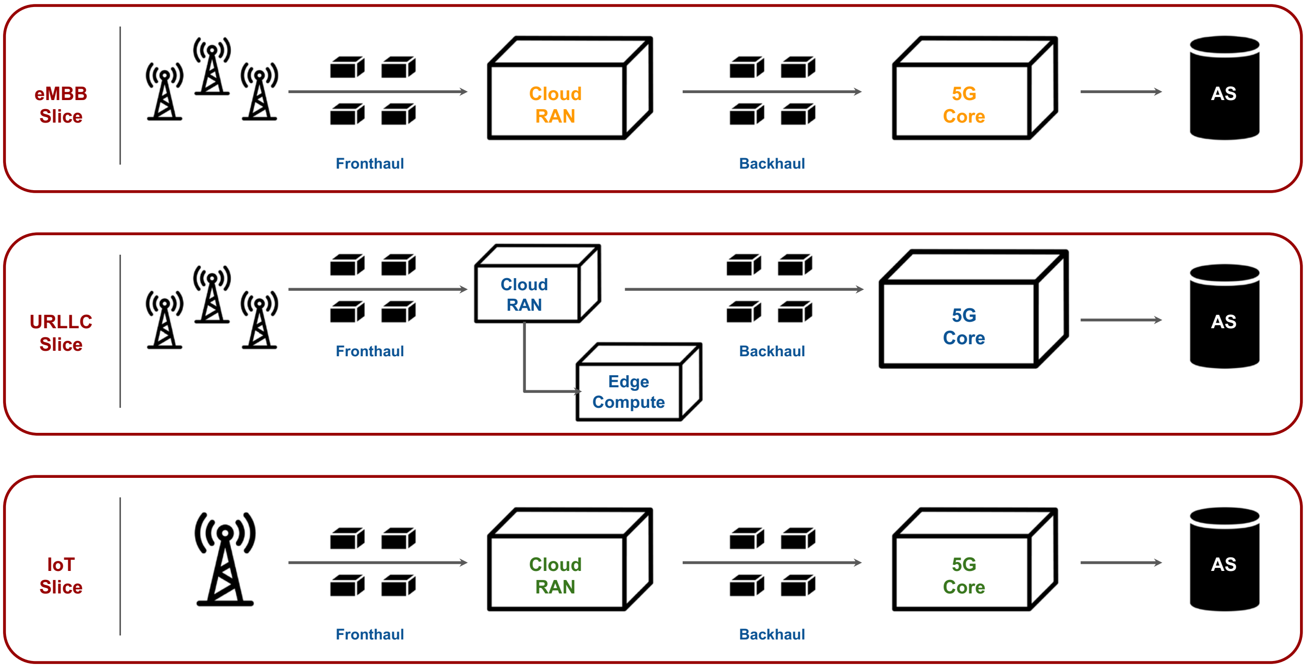


Fig. 9 5G Wireless network slicing for eMBB, URLLC, and mMTC

different slicing is called Ultra-Reliable Low Latency Communications (URLLC) which includes a class of applications such as self-driving car, virtual reality or augmented reality which have very stringent round-trip delay times (RTT) for them to operate efficiently. Some of those applications are mission-critical and need a high degree of reliability. The next slice is called massive Machine Type Communications (mMTC) which includes a category of services like Internet of Things (IoT) where we need to connect an enormous number of devices [38]. These devices may not essentially require extremely high data rates or low latency. They may be short bursty low bandwidth type devices that can do not have specific characteristics of a lot of them, but not necessarily high data rates smart cities smart home wearables are all example of those now.

The logical flow of an end-to-end network slice for infotainment part of a customer (say Honda) is illustrated in the Fig. 10. The budget for the network slice Service Level Agreement (SLA) is 10 Mb/s. The customer portal sends a request to the operator. And the operator uses its network slice blueprints, or templates, to generate a network slice profile. And after that it goes through various decompositions, triggering various actions in the network. The first thing it does is, it sends a request to network function virtualization Orchestrator (NFVO), which is creating the virtual RAN, virtual core, or both, if it is needed. The second portion is, it send out a request to the RAN controller to create the RAN slice and give the personality to the RAN equipment. By the same token, it sends a request to the 5G core controller to create the core slice which is a personality in the core. Lastly, it directs a request to the transport slice controller to create the connectivity between this, RAN and core. At this point, it's stitching all these slices, creating a single end-to-end network slice for a specific customer which is from the service type that is explained before.

Network slicing can be utilized by business customers for their specific requirements by having access to highly customized networks. SLAs can be used for governance of the services in an efficient, timely and cost effective and timely manner [38]. The industry sectors such as automotive, logistic, health and wellness, financial, smart cities, industry 5.0 etc., will have high potential for the application of network slicing [36–42]. However, enterprises prefer private 5G networks over network slicing because of potential security risks involved when slices are procured from a MNO's public 5G networks. Also, private 5G networks can be built and controlled by enterprises using their own spectrum [43]. The enterprise decision on whether to opt network slicing or private 5G will largely depend on the technology's cost, maturity, and trust.

8 Private 5G network-as-a-service

Developing and deploying network services the traditional way using dedicated infrastructure is slow and costly and it is increasingly out of sync with a business world that wants agility and flexibility. High connectivity cost and its's com-

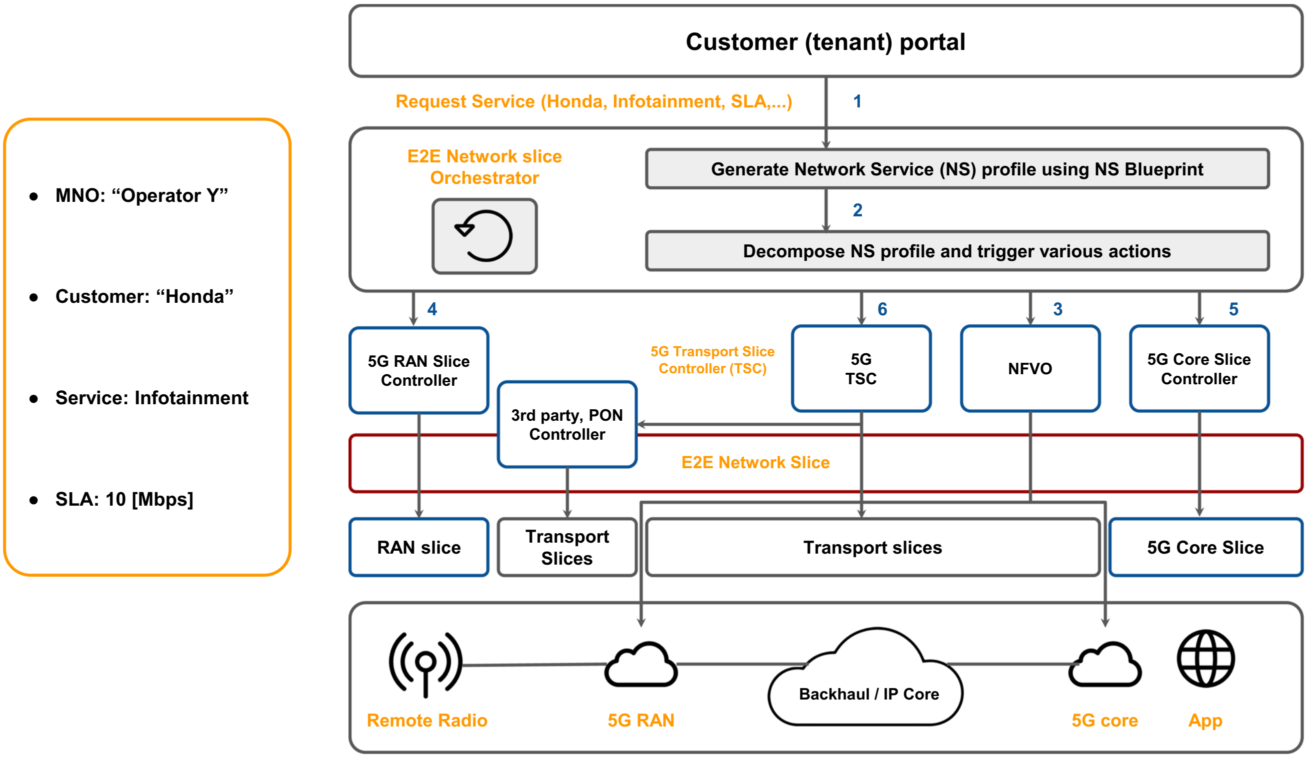


Fig. 10 Logical flow of an end-to-end network slice

plex maintenance due to proprietary solution are the key challenges faced by industry in their digital transformation. The enterprises can manage its end-to-end connectivity with a dedicated infrastructure by deploying a 5G private network [6].

Private 5G network-as-a-service (5G-NaaS) is an Application Programming Interface (API) on top of the network orchestrator which lets third party clients with appropriate IT skills to demand definite network services tuned to their business needs. It develops customized templates accessible for the business clients to specify various requirements in terms of location, duration, QoS, supplementary services, etc. 5G-NaaS model by a provider could be a "Zero Capex", its subscription can be a key enabler for customers in their digital transformation with constrained budget. It is a complete managed solution that empowers MNOs and MSPs to deliver private 5G network services quickly and securely to the enterprise as shown in Fig. 11. It can free up the customers from any type of vendor lock-in, provide more flexibility, competitive pricing, cost-effective scaling, and faster innovation which could significantly lower cost. 5G-NaaS providers can help enterprises experience a carrier-grade private 5G network to operate their mission-critical applications with low latency, high bandwidth, end-to-end security, and enhanced coverage. They can also deliver secure and fast mobility across several enterprise sites. The benefits of 5G-NaaS to the MNO includes [14]:

- Simplified operation and management.
- Flexible deployment models.
- MNO integrated mobility.
- Deep business insights.
- Lowest cost of entry.
- Powerful, scalable, and flexible.
- Data privacy.

NTT, an international business solutions and technology provider have unveiled private 5G network-as-a-service (5G-NaaS) platform, named NTT P5G in August 2021 [44]. It will deliver private network delivering performance, security, control, and complete coverage.

9 MNO's roles in private 5G networks

As discussed in previous section, a private 5G network deployment can generally fit into one of the two categories, an independent physically isolated or integrating the MNO's public 5G network resources. In both instances, a complete private 5G network can be deployed by an enterprise with gNB, 5GC CP, UDM, MEC and UPF within its premises. MNOs offer the network resources (and licensed spectrum) necessary for these private 5G projects with other services such as network management, hardware assistance and planning. However, MNOs play slight or no role in the

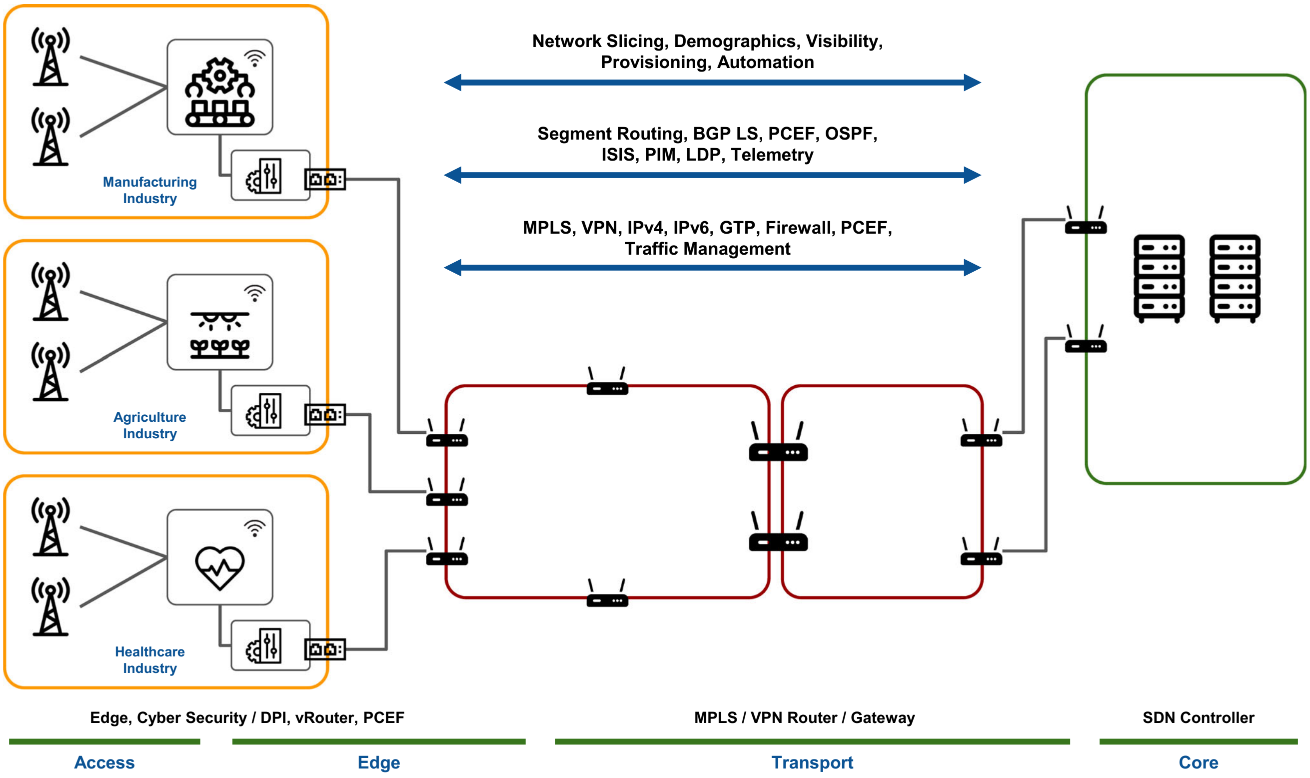


Fig. 11 Private 5G network as a service (5G-NaaS)

deployment of private 5G networks for enterprises, which are instead guided by proven 5G vendors such as Nokia, Ericsson, Huawei, Qualcomm etc. [45]. In this section, the different services and capabilities provided by MNOs are discussed.

Network slicing This can be utilized to create partitions or slices of MNO networks for different use cases or applications, enterprises, or customer profiles [39]. For a local break-out, countrywide slices can be considered and the next-generation MVNOs have potential for geographic slicing, with various network configurations and external control given to third parties.

Spectrum leasing Few MNOs have domestic spectrum licenses can be used to deploy private 5G networks in particular remote areas such as ports, pipelines, agriculture fields, mines, etc. [27]. Spectrum can be assigned to a business or enterprise through a lease or local resale.

Campus networks A dedicated onsite network infrastructure can be provided for major enterprises such as airports, hospitals, and manufacturers. Both outdoor and indoor areas can be covered, a dedicated additional radio equipment can be added for ubiquitous coverage. An independent on-premises core network or a distinct virtual cloud instance can be offered to enterprise for better administrative control and rights. If an MNO is involved, it will be simpler to interoperate the onsite 5G connectivity with WAN.

Shared in-building systems MNOs will collaborate to create, fund, and share indoor wireless solutions for the benefit of the customers. In the UK, Joint Operator Technical Specification (JOTS) Forum facilitate MNOs and their partners to implement high-quality shared wireless private 5G networks [46].

Deployment and operational services MNOs provide a set of network service components to deploy private 5G. They can design and deploy the network systems, but let their technical staff own, manage, and operate them. Various other managed services such as subscriber management, security, RF planning can be provided by MNOs [47].

Cloud-based functions A private 5G network can be built using numerous operational systems, software components, 5G core, radio infrastructure, interconnection with other networks, regulatory compliance and so on. Several vendors are trying to offer cloud-native components directly to the enterprises. MNOs deal with their own multi-tenant cloud resources, possibly hosted in their own EC infrastructure [48].

10 Transforming industry with private 5G networks: use cases

5G has the potential to be a game changer for business enabling innovation efficiency and transformation across industries. 5G private networks are built to help you grab the possibilities in different sectors [53] such as manufacturing [6], logistics and supply chain [49], retail [10], healthcare [50], transportation [18] and much more. Driving innovations such as improved automation, better visibility into supply chain management and new ways to deliver enhanced customer experiences, private 5G networks could make all the difference to a large business. Private 5G can be thought of as a next-gen network service for business driving operational and cost, efficiencies, and elevating business functions from mobile workforces to remote operations and supply chains for manufacturing. This section will give a quick overview of major private 5G use cases in 5 different industries.

10.1 Healthcare innovation

Healthcare is one of the largest addressable markets among the 10 industrial sectors that were analyzed [51]. A critical feature of healthcare IT infrastructure is network connectivity. 5G helps to deliver safe, reliable, efficient, and high-quality healthcare services to all. Transformation of hospital networks through private 5G is essential to improve reliability, maximize coverage and preserve robust security. Private 5G networks offer a self-contained, connected campus of secure, ultra-reliable wireless environment that enables sensors and IoT devices to communicate with each other. For example, a hospital in Wuhan, China, the epicenter of the Covid-19 global outbreak, deployed a fleet of robots to assist healthcare workers and patients by leveraging the features of 5G technology such as reliability, speed, and quality [53]. Malaysian police involved 5G-assisted drones with heat-sensing technology over large crowds for contactless body temperature screening. The world's first medical private 5G network was launched by the China Telecom and West China Second University Hospital, Sichuan Province in 2019 [52]. It would enable high speed and low latency transmission of massive amounts of data and doctors can consult with their colleagues in 27 other locations. With the gamut of 5G-enabled possibilities, private 5G networks would target several distinct use cases such as remote consultation, mobile ward rounds, remote surgery, emergency response, wireless specialist diagnosis, intra-hospital monitoring, etc. in the healthcare space [52]. It will play a critical part in revealing new solutions in diagnostic, preventive, and therapeutic care.

10.2 Public transportation-airports

Industrial-grade private wireless solutions are driving industry 4.0 today and the 5G digital revolution tomorrow. The competition of deploying private 5G in airports have begun [54,55]. Today's digital airport demands to maintain things moving and secure for all kinds of passengers, airlines, customers, retail tenants, ground and baggage handling system companies, and guests. Private 5G wireless networks provides ultra-reliable, secure connectivity that ensures Airport Operations Centre (APOC) operational and situational awareness to enhance efficiency, automation, and responses [54]. Ericsson will deploy a private 5G mobile network at Paris airport for Air France, Hub One and Groupe ADP which covers Paris-Orly, Paris-Charles de Gaulle, and Paris-Le Bourget airports [55]. Nokia partnered with Swedish telecommunications company Telia will bring up the world's first private network at Finland's Helsinki airport to improve airport operations as well as passenger experience [54]. A 5G ready network will be launched at Brussels airport teamed up with Nokia and operator Citymesh. Private 5G networks helps airports minimize the dependency on third-party MSPs and the opportunity to design a reliable and secure infrastructure to achieve digital transformation [55].

10.3 Industry 4.0

5G is the critical catalyst for Industry 4.0. According to GSMA research [10], 5G network technology combined with IoT, Artificial Intelligence (AI), Big data and Edge computing is expected to be a key enabler of Industry 4.0. 5G networks will empower businesses beyond the factory floor, including distribution, supply chain, warehousing, and customer service. An integrated 5G solution can provide reliable and secure end-to-end connectivity to enhance the productivities across the enterprise. Enterprises started opting for private domestic 5G wireless networks over MNOs. The private model offers numerous substantial benefits such as controlling and securing the information, the capacity to optimize networks for their exclusive requirements, the flexibility to upgrade/reconfigure together with growing business objectives. Ericsson, the Swedish manufacturer launched private 5G to target industry 4.0 agreements [56]. It has teamed up with Russia's Mobile TeleSystems (MTS) to deploy its first 5G-ready private network [57] to be used by the world's largest gold producer, Polymetal. A private 5G is deployed for BMW plant at China's Liaoning province by Nokia and China Unicom for smart manufacturing services [58]. This will enable low latency communications for video surveillance, multi-access edge computing to process and analyze data closer to the place where it is used.

10.4 Precision agriculture

Farming is going digital, and the future of the farm will employ more data and less chemicals. New technologies such as 5G and the IoT are allowing practical applications to achieve greater efficiency, environmental protection, and sustainability [59–61]. The possibilities of 5G and real-time data processing will lead to a revolution in the agriculture sector. Sensor data from fields can help farmers identify the need for water in specific areas, have a disease, or require pest management [59]. 5G technology makes it easier to scale networks containing large numbers of IoT devices, autonomous robots, drones, and hence can change agriculture and farming forever [60]. Private 5G networks will bring various benefit such as data management in farming, quality control of crops, cost management, business efficiency and so on [61].

10.5 Dedicated private 5G network deployments

The business enterprises must decide the ways of provisioning different private 5G use cases that deliver real-world Return on Investment (ROI). Several enterprises have already started exploring and, in some cases, deployed them. This benefits each industry with 5G's improved coverage, speed, and capacity. While not every business enterprise requires 5G, almost all large business environments that demand reliable and consistence performance, high availability will benefit from private 5G. The Table 7 summarizes the details of dedicated private network solutions and deployments relating industrial end users.

Table 7 Industry use cases of private 5G network deployments

Industry and year	Industrial end user	5G Infrastructure provider	Features
Manufacturing (2020) [62]	Samsung Austin Semiconductor, Austin	AT&T and Samsung electronics America	Smart manufacturing
Manufacturing (2020) [63]	Haier, China	GSMA, China Mobile & Huawei	Edge computing and performance optimization
Mining (2020) [53]	Yangquan Coal Industry (Group), Shanxi	China Mobile & Huawei	Automation of mining industry
Manufacturing (2020) [10]	BMW plant, Leipzig	Deutsche Telekom & Ericsson	Higher control and reliability functions
Manufacturing (2020) [64]	Ford Motor Company, Essex	Vodafone	Replace WiFi and ramp up the production
Transportation (2020) [65]	Lufthansa Technik, Hamburg	Vodafone	Performance optimization and multi-access edge computing (MEC) addition
Manufacturing (2019) [66]	Mercedes-Benz Cars, Sindelfingen	Telefónica Deutschland & Ericsson	Smart manufacturing for the future
Factory Automation (2019) [10]	OMRON Corporation	Nokia & NTT DOCOMO	Smart factory automation
Manufacturing (2018) [67]	OSRAM, Schwabmünchen	Deutsche Telekom & Ericsson	Enhanced productivity, automation, and flexibility
Manufacturing (2021) [68]	Schneider Electric's plant, Le Vaudreuil	Orange & Nokia	QoS and security of industrial management
Healthcare (2020) [69]	Emory Healthcare, Atlanta	Verizon	Provide remote patient monitoring, telemedicine, medical training
Healthcare (2020) [70]	Samsung Medical Center, Seoul	Korea Telecom (KT)	Apply 5G connectivity solutions to medical diagnosis and treatment
Transportation (2020) [71]	Horiba Mira, Nuneaton	Vodafone	To validate, test and verify self-driving cars

11 Security aspects of private 5G networks

Many enterprises assume that having a private 5G network keeps them safe. However, the attack surface can be exaggerated by going wireless due to various reasons such as physical movement of devices on the network, enlarged IIoT exposure, IoT manufacturers, MNOs/MSPs, suppliers, vendors and so on [72,74]. 5G private networks become a significant part of an enterprise's mission-critical infrastructure and its daily operations, hence making security aspects much more important. A robust layer of security is crucial. Security of 5G private networks can be handled in a two-part approach, (1) public network integrity and availability must be preserved [73], (2) value-added security services are desirable to guard 5G capabilities-based ecosystems.

Security application is also based on the underlying network architecture [78]. The principal components of a private 5G network includes the 5G core's Control and User Planes (CP and UP), Radio Access Network (RAN), and Multi-access Edge Compute (MEC). As discussed in deployment scenarios section, deploying an MNO-independent network is one of the best architectural choices for a private 5G network. It has all four components (RAN, 5G Core, MEC) physically isolated from an MNO's public 5G network. The other option includes deployment of a logically isolated MNO-dependent network where some or all the components may be on the public 5G network. The former option is more secure, but the latter is more cost-effective. Each deployment choice can be viewed from an enterprise vs MNO perspective since profiles such as control, customization, complexity, and agility will differ for each type. The key zones of cybersecurity to address in 5G networks are described in the Table 8.

When compared with enterprise Wi-Fi applications, private 5G networks offer more advantages. It is easy to deploy, less vulnerable to interference, harder to eavesdrop and more reliable. 5G industry experts predict that Wi-Fi and private 5G could provide benefits altogether. The telcos have an opportunity to offer Security-as-a-Service (SecaaS) as a companion to the private 5G network [81].

12 Open-source projects for private 5G networks

Today 5G is rolling out around the world with wide adoption much faster than previous generations. A lot of new capabilities and enablers for fundamentally new use cases that were never possible before in previous generations. Hundreds of millions of devices already shipped and billions coming in the next few years and hence this is a significant progress at a rate that exceeds any other previous generation that we have seen. At the same time, the RAN architecture and deployment models are evolving equally and rapidly. Today most of the world is based on traditional RAN architectures where there are basically closed systems that include a core network that may have a somewhat open interface via the backhaul to the RAN, but the entire RAN is implemented by typically a single vendor or a small number of vendors working closely with many proprietary interfaces. As the sprint towards 5G have begun, there is advent of open-source projects such as Magma core [82], srsRAN [86], Aether [84], particularly in telecommunication world. In this section, various open-source projects that are offered for building open-source RAN targeting the user equipment (UE) are discussed.

12.1 Magma core

Magma is an open-source packet core project supported by leading open-source foundations. The magma project is the open infrastructure foundation collaborating with the Open Core Network (OCN) project group and the OpenAirInterface software alliance to bring magma to an independent open-source project and foster its development as the leading open-source wireless data core. The internet has become a crucial tool for improving livelihoods and magma strives to facilitate bringing connectivity to places where it has not generally been available in the form of private 5G networks. Magma's mission is to bring more people online by facilitating MNOs/MSPs with open flexible and extensible carrier-grade networks. It is a distributed and scalable wireless data core, and it delivers converged core supporting the major components of a 4G Evolved Packet Core (EPC) and managed Wi-Fi service support for 5G with using the services-based architecture. The software is free for anyone to download, and it will run on most generic computer hardware or on the Cloud. It can also connect to any 3GPP compliant equipment so that any end user can mix and match equipment from different vendors and use different technologies from Wi-Fi to 4G LTE, 5G and beyond.

Magma also has rich APIs to easily connect to end user's existing infrastructures and they can manage them all from a single pane of glass. The enterprises needn't invest in expensive hard to use packet cores and avoid vendor lock-in forever since Magma is supported by a rich open-source community [89]. It is easy to add new features and capabilities. The developer community is organized by leading open-source foundations and is adding new features to Magma every day. An enterprise or end user can request for help from community if they have an idea for a new feature or new requirements. Finally, the enterprise has the technology to extend their network with any equipment vendor they want, at a super low cost and without disrupting their current operations. Enterprises can join the community of service providers around the world that are bringing a faster internet to people everywhere.

12.2 5G OpenRAN

Open radio access networks (OpenRAN), also called Open disaggregated RAN uses open, interoperable interfaces and protocols to deploy private 5G mobile networks [83]. It provides improved flexibility over traditional RAN and an alternative way of deploying networks that guarantees vendor competition, multi-vendor interoperability, reduced operating costs, security across RAN. OpenRAN emphases mainly on vendor-neutral software and hardware using community-developed standards and open interfaces, providing MSPs the capability to use radios of one provider with another provider's RAN applications. With 5G mobile network deployment happens in full-swing, MSPs around the world are utilizing the opportunity to transform their private mobile networks. The deployment of private 5G networks have unique requirements with respect to available spectrum, processing hardware, space, environment, etc. OpenRAN solution offers flexibility, multi-vendor hardware and software choices as per the enterprise use cases and deployment circumstances. It includes three primary elements, namely, the Radio Unit (RU) integrated into active antenna, the Distributed Unit (DU) centralized or at cell site and the Centralized Unit (CU) where packet processing takes place. The interfaces among these elements are the main emphasis of OpenRAN.

The increase in demand for private 5G network provides new business openings for MNOs to monetize their invest-

Table 8 Threat landscape in private 5G networks

Key zones of 5G networks	Threats/attacks
RAN to core risks	Man-in-the-middle (MITM) attacks [76]
	Rogue gNBs [74]
	Internal threats and malware [75]
	IoT signalling storms [77]
5G Core and automation	Network slice security [78]
	Improper access control [80]
Application programming interface (API) exposure risks	Data exposure [79]
	Denial of service (DoS)/distributed DoS attacks [73–75]
	Authentication hijacking [73]
	Injection attacks [78]
Service platforms and applications risks	Malware [78]
	OWASP top 10 vulnerabilities [79]
Air Interface threats	MITM [76]
	Jamming [81]
Passive attacks	Mobile identity capture [72]
	Uplink/downlink impersonation [78]
Connected device threats	Bidding Down (service degradation) [78]
	Malware [80]
	Device tampering [81]
	Intercepting communication [81]
	Sensor vulnerability [78]

ment in network infrastructure and spectrum allocation. Open RAN can enable different services and enterprise use cases with energy-efficient installation and minimum equipment. Especially in fifth generation, it can act as a future-proof, cost-efficient solution for MNOs to maximize the annual Return on Investment (ROI). The 5G industry's first 3GPP Release 16 5G Open RAN platform was announced by Qualcomm which is its second-generation 5G RAN Platform for Small Cells [90]. It supports a lot of features such as URLLC to provide link reliability (up to 99.9999%) and low latency desirable for industrial automation and mission critical infrastructure, the demands of private 5G networks, sub-6 GHz deployments.

12.3 ONF's Aether platform

Open networking foundation (ONF) unveiled "Aether", the first open-source platform for enterprise 5G connected Edge-Cloud-as-a-Service, optimized for unlicensed, lightly licensed (CBRS) and licensed spectrum [84]. It provides three fundamental services, namely, the private 5G connectivity service with an on-premises local breakout and enables low-latency mission-critical applications, keep the backhaul requirements at bay and enables programmatic traffic localization and privacy building. On this service is the connected edge cloud service, a service that natively allows 5G connectivity to edge cloud applications. The next is network end-to-end slicing, the capability for the enterprise to easily assemble and execute policies for different flows, flow types and subscribers. Aether is cloud managed and easy to deploy operationalize configure observe and controlled by the enterprise. All aether services are programmable by the enterprise with easy-to-use interfaces. The private 5G connectivity service enables QoS differentiation which ranges from low latency mission critical services to best effort services. Programmatic network slicing brings another dimension for such differentiation coupled with programmatic access control. The connectivity service also brings cellular network-grade sim-based encryption to the enterprise network as a connected edge cloud platform. Aether is uniquely built on a Software Defined Networking (SDN) infrastructure that enables programmable forwarding and it supports Artificial Intelligence (AI) or Machine Learning (ML) driven IoT and Operational Technology (OT) driven applications.

12.4 ETSI OSM

Open-source MANO (OSM) is an European Telecommunications Standards Institute (ETSI) held project to build an Open-source Network Function Virtualization (NFV) Management and Orchestration (MANO) software stack affiliated with ETSI NFV [85]. NFV suggests an architecture that lets

MNOs to virtualize network functions in an automated, high-performing, and elastic manner. The use cases are associated with 5G private mobile networks and OpenStack acts as a Virtualization Infrastructure Manager (VIM) for most of the implementations. Open-source projects such as Open-Source MANO (OSM) and Open Networking Automation Platform (ONAP) assists the private network service across the various sites connected through high bandwidth, high capacity and ultra-low latency delivered over 5G networks. 5G-Transformer is an open-source project based on OSM which brings network slicing into transport networks by providing orchestration and slicing for business verticals such as healthcare, automotive, media, etc. [88]. These projects based on OSM demonstrates the real-life business use cases of 5G technology over NFV and indicates effective 5G implementations by industry verticals.

12.5 srsRAN

srsRAN developed by Software Radio Systems (SRS) is an open source 4G/5G software radio suite [86]. It can be employed with third-party core network solutions to develop entire end-to-end LTE wireless networks. It includes a full stack 5G-Non-standalone (NSA) software radio UE (User Equipment) application for deploying private 5G networks. It runs as an application on a Linux-based operating system and offers a standard LTE network interface with high-speed performance and mobile connectivity. The basic architecture of srsUE includes layer 1, 2 and 3, where physical layer is at the bottom and Media Access Control (MAC) and Radio Link Control (RLC) exists on the layer 2. At layer 3, we have Radio Resource Control, Non-Access Stratum (NAS) and Gateway (GW). srsRAN helps to attain high performance in 5G without the help of dedicated hardware accelerators. srsUE works fine with network equipment from Nokia, Huawei, Amarisoft, etc.

12.6 OpenAirInterface UE

OpenAirInterface's (OAI) role in establishing a 5G reference architecture for the emerging 5G industry is very crucial [87]. It is an open-source implementation of User Equipment (UE) that operates on platforms such as ARM/Intel targeting towards the forthcoming 3GPP Releases. It serves as a standard for 3GPP Release13/14 development towards 5G. Some of the important proposals include massive MIMO, LTE-LAA, NarrowBand-IoT, etc. OAI 5G stack is divided into three use cases, namely, OAI-CN (OAI Core Network), OAI-RAN (OAI Radio Access Network), MOSAIC5G and these are distributed under independent licenses. It supports NSA gNB software stack which is essential for private 5G networks.

13 Research directions in private 5G networks

5G rollout is ongoing and experts predict that 5G network deployments will gain momentum from 2020 and beyond. The public across the world are waiting for 5G compatible devices and this new technology is continuing to mature. Organizations are discovering research areas and challenges in 5G technology, serving to produce breakthroughs in this technology, its applications, and consequences. 5G technology delivers a transformative experience with its benefits including faster connectivity, higher data rates, possibly lower power consumption, potential to benefit enterprises, end users and consumers, and everybody in between. This section emphasizes on the major research challenges and directions surrounding the deployment of private 5G technology.

13.1 Spectrum harmonization and massive MIMO

Wave spectrum challenges are generated due to 5G global advancements and changes. The prospective goal for 5G technology is to deliver the necessary bandwidth to every user with a compatible device. Private 5G networks can offer this bandwidth by means of a frequency spectrum above 6 GHz. Researchers are discovering the new opportunities of spectrum and high frequency channels for private 5G communications. The 5G NR-U unlicensed spectrum range between 5GHz and 6 GHz which is very short range. Signal obstruction can be caused by objects such as building, trees which necessitates several cell towers to evade signal path loss. Researchers are entering into multiple-input, multiple-output (MIMO) technology which proves to be an effective and simple solution for 5G connectivity expansion and signal path issues [91]. An immense MIMO network is more resistant to jamming and signal interference.

13.2 Network optimization using machine learning

The private 5G systems can use novel and existing Machine Learning (ML) algorithms to optimize its operations. Artificial Intelligence (AI) or ML techniques are applied in 5G automation, network slicing, network planning, reduce operating costs, etc. [92,93]. It can also be used across all layers such as 5G Core, RAN and more. There are three key research directions with respect to this. (1) Enhancing 5G system usage by the end devices: As demanded by the end users and the markets, the end devices in a 5G network will not be equally treated. ML can be used to control and optimize the user mobility patterns, network congestion prediction at definite locations. This will result in an improved scheduling of the CP procedures, allocation of the resources, eventually, a better network service is provided. (2) Optimizing the network management [94]: ML can also provide insights about the functioning of the private network which leads to effective performance, fault, and security management. Many parameters can be monitored for an extended duration of time which could help in optimization of anomaly detection, performance degradation, fault discovery, security, scaling, network elasticity and mitigation solutions in 5G private network systems. (3) Slighter human interaction: Network operations can be executed without vastly educated experts with lesser human interaction required to look the network and to set the governance policies.

13.3 Enterprise use case customization

Customized 5G private deployments for different use cases ought to be enabled by considering the probable sizes and communication environment. The following operations have to be accomplished for each use case customization including (1) integration with 5G RAN equipment from many radio providers. (2) End-user equipment-based integration by retrofitting the use case devices to the 5G modems. (3) Use case specific applications integration which covers the expected communication data paths for the use cases.

13.4 Security and robustness

Security is rapidly becoming a key area of research focus during global 5G network rollout [72–75]. Private 5G networks can be trusted if it can be protected from failures, attacks, defects, or misconfigurations. Scaling and flexibility bring a new set of challenges in terms of robustness of the overall private networks. The research challenges include:

- Automation of fault management for dynamic 5G environment can be achieved by monitoring components.
- High availability and load balancing of CP and data path.
- Mission-critical infrastructure robustness of private 5G environments.
- Sharing state information between components of private network for high availability.

13.5 Battery and storage technologies for 5G equipment

Longer battery life and improved energy storage technologies are essential for end users to relish the full potential of 5G technology. Research on lithium-ion battery technology is carried out to enhance the battery life and 5G equipment optimization for user prospects [94]. A 5G network with local gNB will intensely increase computation speeds and empower the transfer of data from smartphone to the cloud. Present 5G based smartphones want to preserve a connection to multiple networks such as 5G, Wi-Fi which contributes to mobile battery drain. The existing limited infrastructure of 5G worsens this problem. As 5G technology remains to increase worldwide, enhancing the battery life and energy density will be vital.

13.6 5G NR small cell research

5G NR small cells are low-powered radio access points that supports ultra-low latency, massive 5G network speed, coverage and capacity which are essential features of a 5G network [95]. The telecom industry is anticipated to rely on small cells as building blocks to efficiently scale 5G NR networks. These small cells can deliver uniform 5G experiences, particularly indoor environment where most data are consumed. As MNOs look to provide better 5G experience to the users, small cell research is gaining momentum [96]. The faster small cell research progress, the consumers will have 5G devices sooner connected to 5G-only internet.

13.7 Network slicing for private 5G

Network slicing makes things simpler, and it is still challenging to share resources to different slices [23]. This is because the private 5G networks will be complex, and it'll be changing constantly. The usual method of sharing out resources can't easily adapt to a constantly changing network it's time-consuming and not very effective. As an evolving technology with several advantages for private network deployment, network slicing has increased many research challenges for the networking industry and the enterprises [97–99].

14 Conclusion

3GPP-based private 5G networks are dedicated networks which offers irresistible benefits to the enterprises. It is gaining momentum as regulators allocate additional spectrum including NR-U to help enterprises build and maintain their own private 5G networks. It is a game-changer for critical enterprise applications such as industry 4.0, healthcare, smart cities, etc. which expects digital transformation. The current deployment scenarios indicate that most of the dedicated private 5G network deployments will involve the presence of MNOs in some way. This survey paper presents an overview of the private 5G networks, its enabling technologies, spectrum allotment, use cases, and the latest research issues addressing different facets of the private 5G deployment. This, in turn, should deliver a great foundation for 5G network practitioners, academicians, and researchers who are interested to receive an insight into the private 5G technologies and to understand the complete architecture. Moreover, the interplay between the different wireless technologies such as 5G, private 5G, and Wi-Fi 6, has been discussed. Through critical 5G wireless private networks, enterprises can more rapidly realize and realize digital transformation.

Author Contributions All authors contributed to the study conception and design. Data collection and analysis were performed by Sivaraman. The first draft of the manuscript was written by Sivaraman, and the contributing author commented on improving the quality of manuscript. All authors read and approved the final manuscript.

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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