Private 5G Networks: Concepts, Architectures, and Research Landscape

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TR2022-036 May 19, 2022

Abstract

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IEEE Journal of Selected Topics in Signal Processing 2022

Private 5G Networks: Concepts, Architectures, and Research Landscape

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***Abstract*—A private fifth generation (5G) network is a dedicated 5G network with enhanced communication characteristics, unified connectivity, optimized services, and customized security within a specific area. By subsuming the advantages of both public and non-public 5G networks, private 5G networks have found their applications across industry, business, utilities, and the public sector. As a promising accelerator for Industry 4.0, the concept of a private 5G network has recently attracted significant research attention from industry and academia. This article is one of the first attempts to provide a comprehensive view on the research in private 5G network. Specifically, this paper first provides an overview of the concept and architecture of private 5G networks. It then discusses implementation issues and key enabling technologies for private 5G networks, followed by their more appealing use cases and existing real-life demonstrations. Finally, it examines some research challenges and future directions regarding private 5G networks.**

***Index Terms*—5G, private networks, non-public networks, Industrial Internet of Things (IIoT), Industry 4.0.**

I. INTRODUCTION

The fifth generation (5G) cellular networks are being rolled out across the world. 5G networks are shaping the industrial world as well as our daily lives, enabling many new applications, through multi-Gbps peak rates with ultra-low latency and ultra-high reliability [1]–[4]. However, public 5G networks, owned and operated by mobile network operators, also face important challenges for wide-spread adoption. Coverage is one of them. Mobile network operators tend to deploy networks in areas with large numbers of subscribers in pursuit of revenue to cover deployment costs. This may result in poor network coverage in less populated urban areas and an even no coverage in more remote zones. Coverage may also be unsatisfactory in indoor locations with harsh radio frequency (RF) conditions. Moreover, in a world where data breaches and cyber attacks frequently occur, high-technology industrial companies require the use of their own customized security policies and locally stored data, which may not be supported by some of the traditional public cellular networks. As a result of these shortcomings, private networks, which are also termed non-public networks in the 3rd Generation Partnership Project (3GPP) [5], have attracted significant interest.

Private networks are not merely a theoretical construct. Although still in their early stages, they do exist today. For example, private Long Term Evolution (LTE) networks, which build on fourth generation (4G) technologies, are currently a commercial reality [6]. By taking advantage of the global LTE ecosystem, private LTE networks are able to support many industrial applications in different sectors, by accommodating and processing the information gathered through a large number of sensors, actuators, robots, security cameras, etc. However, industries have increasingly stringent performance requirements, regarding throughput, latency, reliability, availability, security, and device density [7], which private LTE networks cannot meet. For instance, the performance requirements for the link between control systems and physical actuators are extremely demanding and cannot be met by LTE technologies [8]. Although wired technologies such as field bus communications could still be used to satisfy this type of use cases, they require high maintenance costs and fail to provide the mobility required by future industries. In particular, as Industry 4.0 evolves, the factory of the future will involve massive numbers of Internet of Things (IoT) and Industrial IoT (IIoT) devices for mission-critical applications [9], rendering wired solutions inefficient. The deployment of non-public 5G networks is thus a logical evolution —and better fit— for the above industrial needs [10].

In airports, non-public 5G networks are making some new technologies possible, including mobile safety systems and real-time, automated, and contactless passenger screening systems. For mines that are usually located in remote and underserved areas with no public network coverage, private 5G network can be established to improve productivity and safety without the need for a mobile network operator. In campus environments, private 5G networks are allowing owners to track assets and customize their desired services. Besides, airports, mines, and campus environments like universities, hospitals, and military bases would benefit from these private

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TABLE I
COMPARISON BETWEEN WI-FI 6 AND PRIVATE 5G.

	Spectrum	Coverage	Reliability	Mobility & off-site	Security	Outdoor suitability	Cost	Application scenarios
Wi-Fi 6	Unlicensed	Local	Low	Low	Low	Low	Low	Non-mission-critical
Private 5G	Licensed	Wide	High	High	High	High	High	Mission-critical

5G networks [11]. For example, to cope with the diversified military applications and to improve military operation efficiency, 5G-based private network for military operation are being heavily studied [11].

It is worth noting that the new generation of Wi-Fi, namely Wi-Fi 6, has also being able to significant improve capacity and data rates over previous Wi-Fi generations, and has become a candidate for wireless connectivity in industry verticals [12]. In Table I, we make a comparison between private 5G and Wi-Fi 6 in terms of spectrum, coverage, reliability, mobility, security, outdoor suitability, cost, and application scenarios. As shown in Table I, the main benefit of Wi-Fi 6 lies in its low deployment cost, especially on the client side.

Unlicensed spectrum is not a resource only accessible through Wi-Fi devices, but also through cellular ones. Indeed, 3GPP Rel. 13 and 14 standardized three different approaches for cellular technology to leverage unlicensed spectrum, namely, LTE wireless local area network (WLAN) radio level integration with IPsec tunnel (LWIP), LTE-WLAN aggregation (LWA), and Licensed-Assisted Access (LAA) [13].

- When using LWIP and LWA to leverage the unlicensed spectrum, a cellular network gets access to such unlicensed channels through inter-worked Wi-Fi access points (AP). In LWIP, the interworking split of packets between Wi-Fi and cellular paths occurs at the internet protocol (IP) layer, while in LWA, it takes place at the packet data convergence protocol (PDCP) layer. The former is more universal as it works with any Wi-Fi AP, while the latter provides a tighter control among others by splitting packets between the Wi-Fi and cellular paths due to the standardized LWA user equipment (UE) feedback and other tools.
- In contrast, when using LAA to leverage the unlicensed spectrum, cellular technology, and not Wi-Fi, is directly used to get access to the unlicensed channels. Importantly, it should be noted that LAA requires a licensed carrier to be paired with the unlicensed one to manage the control plane. Moreover, it is worth mentioning that LAA adopted an unlicensed channel access protocol very similar to that of Wi-Fi, i.e., carrier-sense multiple access (CSMA), thus mitigating Wi-Fi/cellular coexistence issues.

Note that 3GPP further developed a new technology to allow access to the unlicensed spectrum in its Rel. 15 and the following one, a.k.a. new radio-unlicensed (NR-U). This technology, which builds on the former ones, i.e., LWIP/LWA/LAA as well as on MuLTEFire, an industry standard developed by some major vendors and operators, presents a significant advantage over its predecessors. It is a stand-alone technology, which does not require any licensed carrier to operate in the unlicensed bands. Moreover, NR-U APs can take advantage of many of the new sophisticated cellular 5G features, as will be detailed later [14].

To overcome coverage-related issues, an increasing number of residential Wi-Fi customers are deploying APs with multiple antennas in their homes, since their beamforming capabilities offer an extended coverage range compared to their single-antenna counterparts. To further enhance mesh solutions that use a master AP, which is connected to the wired Internet connection and shares this connectivity with the extender APs through a wireless backhaul connection, the Wi-Fi industry has introduced in recent years more sophisticated consumer mesh products, based on the 802.11s mesh WLAN networking standard. These mesh-based solutions still rely on the basic principle of increasing Wi-Fi coverage through the use of a master AP providing wireless backhaul to extenders, but they are capable of providing an enhanced end-user experience thanks to features such as seamless roaming between APs, and automated configuration of the mesh network [15].

IEEE 802.11be, the standard Wi-Fi 7 over which the next generation Wi-Fi is going to be built, presents a number of enhancements, which will help to reduce latency and enhance reliability. Indeed, the better multi-band capabilities specified in IEEE 802.11be to take advantage of the large available bandwidth in the 6GHz band will significantly reduce latency and enhance reliability. The more spectrum and better management inherently result in faster channel access, reduced interference and higher user throughputs. Gaming companies have also pushed for specific enhancements in IEEE 802.11 to reduce latency, with a specific focus on the reduction of signaling overhead, e.g., in multiple-input multiple-output (MIMO) procedures, with the consequent channel access and latency benefits. Having said that, private 5G networks running over licensed spectrum have an unquestionable advantage in terms of reliability over Wi-Fi ones running over unlicensed bands. Time to channel access is reduced in highly loaded scenarios, since the base stations do not require a listening-before-talk procedure. Moreover, given that all base stations operating in a given spectrum band belong to the same operator, network coordination can be efficiently implemented to further reduce time to channel access and interference and increase user throughputs. Moreover, 5G base stations can take advantage of their usually more sophisticated medium access control (MAC) layer as well as ultra-reliable low latency communication (URLLC) features specified in 3GPP Rel. 15/16/17 to optimize latency and reliability. Among such features, let us highlight [16]:

- Low-latency features:
  - Higher subcarrier spacing, with shorter transmission durations.
  - Frequent physical downlink control channel (PD-

  CCH) monitoring reducing the latency of the layer-1 control information.
  - Mini-slots with a fewer number of symbols.
  - Configured-grant, which allows the UE to autonomously transmit uplink data without having to send a scheduling request and wait for the uplink grant.
  - Downlink preemption.
- Higher reliability features:
  - Multi-slot repetition.
  - Low spectral efficiency MCS/CQI tables.
  - PDCP duplication.

When comparing NR-U and Wi-Fi 7, these benefits disappear, as the unlicensed spectrum is shared with unknown and uncontrollable nodes. Still NR-U may have some benefits as it can take advantage, as mentioned earlier, of its advanced MAC protocols and URLLC features. However, it is important to highlight that private 5G, Wi-Fi 6, and Wi-Fi 7 networks are expected to coexist and complement each other. In this survey, we only focus on private 5G wireless networks.

A. *Private 5G Networks*

Built on 5G technologies, a private 5G network is a local area network for dedicated wireless connectivity within a specific area [17]. More importantly, it can be independently managed by its owner, who can control every aspect of the network totally, such as priority schedule, resource allocation, security, etc. Enterprise users are allowed to define their own security strategies, and keep sensitive and proprietary data local. Unlike Ethernet, a private 5G network gets rid of costly and bulky wired equipment, being able to connect a large number of devices in a dynamic environment where people and objects are on the move. Compared with private LTE networks, private 5G networks enjoy advantages in both the radio domain and the system architecture. In the radio domain, private 5G networks provide spectrum flexibility, multi-Gbps peak data rates, ultra-low latency, ultra-high reliability, and massive connectivity. At the system level, vertical network slicing, private edge computing, and improved security are essential to realize a truly isolated private 5G networks. It should be also noted that private 5G network subsumes many of advantages from public 5G networks, and importantly, simplifies a significant number of challenges, such us that of interference management. In summary, reusing 5G technology, private 5G networks are characterized by:

- *Practically constant availability*: Communication service availability is defined as the percentage value of the amount of time the end-to-end (E2E) communication service is delivered according to an agreed quality of service (QoS), divided by the amount of time the system is expected to deliver the E2E service according to the specification in a specific area. In private 5G networks, it ranges from critical values (e.g. 99.999999%) to modest ones (e.g. 99.9%), depending on use cases [18].
- *Ultra-high reliability*: Reliability refers to the ability of the communication service to perform as required for a given time interval, under given conditions. Especially, for an industrial automation, wireless IoT and IIoT systems require ultra-high level reliability to successfully execute required tasks within certain constrains as those in the wired systems.
- *Ultra-low latency*: Ultra-low latency refers to the capability of a network to facilitate highly critical applications demanding less than a millisecond level E2E latency in their packet transmissions. This is of great importance for industrial automation, and opens a new door for safe human-robot interaction, e.g. humans and automatic vehicles within a factory. In 5G, to minimize latency, each step of the uplink and the downlink transmission processes has been redesigned by taking into account this latency requirement. In this line, 5G New Radio (NR) employs new numerology, fewer allowed retransmissions, edge computing, and efficient scheduling algorithms.
- *Huge device density with a high throughput*: Many vertical applications in private 5G networks will require the serving many heterogeneous stationary, ad-hoc, and mobile devices such as sensors, actuators, programmable logic controllers, mobile robots, cameras, and augmented reality (AR) and virtual reality (VR) related devices, to cite a few. For example, to support a successful delivery of messages within a certain time, massive connectivity is required. Massive connectivity supporting multi-Gbps peak data rates will be necessary for performing high speed and high precision machine tasks, non-interrupted seamless multimedia service, and efficient collaboration among mobile devices.
- *High security*: private 5G networks can use network isolation, data protection, and device/user authentication to protect critical assets. As a benefit, enterprises or the operating entities gain the data sovereignty and keep sensitive data local. Secure transmissions over the public networks will be critical for military and many industrial applications.

In addition to the mentioned native 5G features, which can also be found in public 5G networks, the unique features of private 5G networks are:

- *Customized predictable QoS*: Performance indicators (e.g., throughput, latency, and packet loss rate) can be better controlled in private 5G networks. Besides, the system performance and resource usage for different vertical services can be tailored to specific requirements in the network based on the local statistics. Although private 5G networks are relatively independent of public 5G networks, there may be a need for inter-enterprise communications via non-public and public 5G networks in some use cases. For instance, service continuity is required when an ambulance moves from a factory that is served by a private 5G network to the outside that is served by a public 5G network. The same should be the case for seamless video service.
- *Consistent Machine Learning (ML) models*: Private 5G networks will present a set of actors and behaviors that are statistically consistent, unlike public networks where the users and scenarios can exhibit a large statistical

variation. To elaborate, different private industrial setups will have a certain structural similarity, suitable to be addressed through multi-task learning. An example of this would be the use of meta-learning: relying on the data from other industrial setups to optimize the local operation, but still adapting it to match the uniqueness of the local conditions. This was shown in the recent paper [19], where meta-learning across several industrial setups is used to predict the blockages in the wireless channel. While distributed ML is not exclusively relevant for private networks, a set of private 5G networks that have different owners and intend to preserve data privacy is an exemplary case for using privacy-preserving distributed learning schemes. In addition, due to a less variable application demand, a shallow AI that employs either ML or reinforcement learning (RL) can be used for resource allocation. When a big domain shift exists between network environments, domain adaptation [20] can be used.

The revolutionary objectives and the consequent advantages of local and private 5G networks are empowered by new architectures and technologies. In [21], 3GPP analyzed some use cases that rely on local and private 5G networks. Based on such analysis, 3GPP proposed two basic architectures for private 5G networks, namely stand-alone and public network integrated paradigms. In [18], the 5G Alliance for Connected Industries and Automation further identified three deployment options for public network integrated private 5G networks. In addition to such new architectures, key enabling developments and technologies for private 5G networks include spectrum management, ultra-reliable low latency communication (URLLC), integration with time sensitive networks (TSNs), vertical network slicing, interference management, localization and tracking, and private edge computing. Despite of their advantages, private 5G wireless networks also present some number challenges. The aim of this survey is to provide an initial overview of such challenges as well as the latest results and progresses in private 5G networks. Particularly, Section II describes the basic concept and architecture of private 5G networks. Section III presents implementation issues of the network. The most important key enabling technologies are analyzed in Section IV. Sections V and VI present key use cases and real demonstrations, respectively. Finally, new challenges and future research directions are discussed in Section VII. The conclusions are drawn in Section VIII.

II. BASIC CONCEPT AND ARCHITECTURE

A private 5G network is usually exclusively designed for a single organization, typically an industrial enterprise. Within the defined premises (e.g., plant and campus), the private 5G network offers network services to devices (e.g., mobile robots, auto-guided vehicles, and various sensors). In the deployment of private 5G networks, many factors need to be considered, including the spectrum, the owners and operators, and the trust level between the private and public network operators. Besides, the availability of solution components and economic feasibility should be taken into account. According to 3GPP 5G R16 [21], which drives 5G into industry expansion, private 5G networks have two basic forms, i.e., stand-alone deployment and public network integrated deployment. which will be surveyed in the following. We also note that the Open Radio Access Network (O-RAN) Alliance has recently introduced the O-RAN concept, which can organize a cost effective and agile RAN by adopting open interfaces, open hardware, and open source. This framework can thus maximize the use of common-off-the-shelf hardware and merchant silicon to minimize the installation cost of the private network. Moreover, it ensures the use standardized interfaces in a multi-vendor network [22], and as a result, O-RAN may be a valuable proposition to build small, customized private 5G networks that are not dependent on a single vendor.

A. *Stand-alone Deployment*

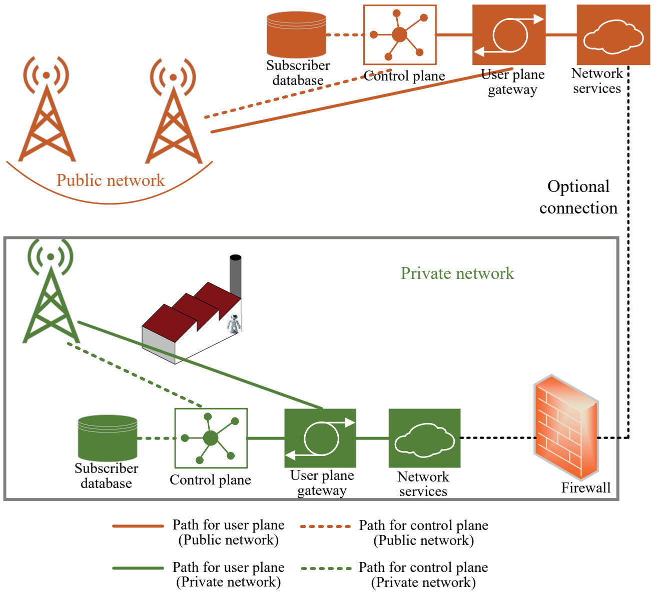

Fig. 1. Deployment as isolated network. (Adapted from [18])

In this scenario, a private 5G network is deployed as an isolated and independent system without dependence on a public network, which is called stand-alone non-public network as well. As shown in Fig. 1, all network functions of a stand-alone non-public network are confined in the logical perimeter of the defined regions. The authors in [23] listed three facts that manifest the independence between a stand-alone private 5G network and a public counterpart. The first one is that the private 5G network uses an unique identifier entirely independent of that for a public network, while the second one is that the private 5G network is usually assigned private spectrum. The last one is that a full deployment of a 5G system (including the RAN and the core network) exists within the logical perimeter of the private 5G network.

Although a stand-alone private 5G network can operate independently, the devices from the private network sometimes still have a need to access public network services. To meet this demand, a connection between the private and public networks can be optionally set up via a firewall.

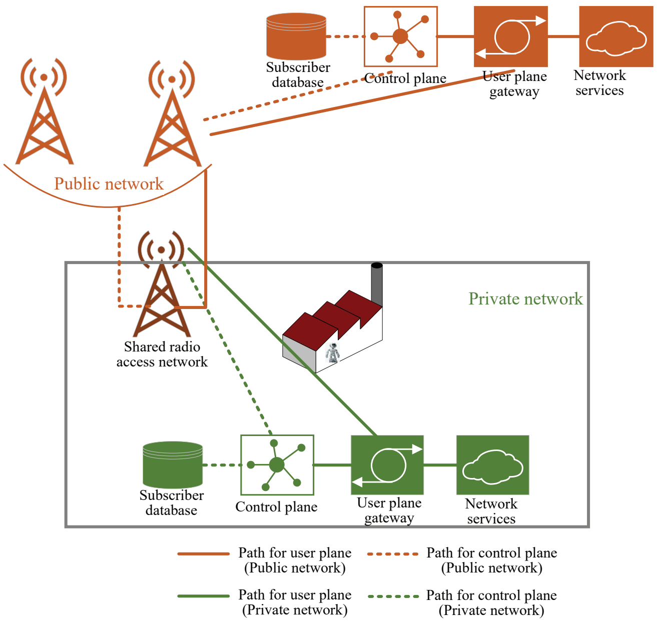

Fig. 2. Deployment with shared RAN. (Adapted from [18])

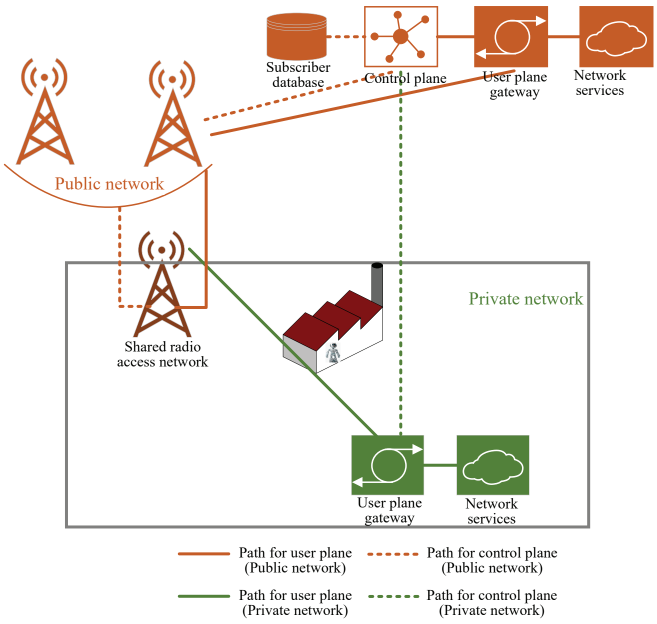

Fig. 3. Deployment with shared RAN and control plane. (Adapted from [18])

B. Public Network Integrated Deployment

In this scenario, a private 5G network is deployed with the support of a public network. The private and public networks are not physically isolated. Consequently, compared with the stand-alone deployment, this deployment has lower customization, self-control, and security. Depending on the levels of integration, this type of non-public 5G networks can be further divided into three cases [18].

1) Shared RAN: As shown in Fig. 2, in this case, the private and public 5G networks share part of the RAN, while other network functions are still separated, and all data flows of the non-public 5G networks are restricted to the local area. For the sake of simplicity, there is only a single base station (BS) for the shared RAN on the defined premises in Fig. 2. However, additional BSs that are exclusive to private network users can be configured. Note that such deployments can be enabled by the RAN sharing concepts already included in the 3GPP specifications [24].

2) Shared RAN and Control Plane: Similar to the above case, the non-public 5G network shares part of the RAN with the public network. Moreover, network control tasks are always conducted by the public network. However, all traffic flows of the private network still remain within defined areas. This approach is shown in Fig. 3, and can be implemented by using vertical network slicing [25], which is a means for creating logically independent networks over the same physical infrastructure. The non-public and public networks have different slice identifiers. Indeed, devices in the non-public network are subscribers of the public network, which are able to connect to the public network and associated services directly.

3) Hosted by the Public Network: In this case, the private network is entirely hosted by the public network. The traffic from both the public and private portions are outside of the defined premises. As shown in Fig. 4, all data flows of the non-public network are guided to the public network via the shared RAN. However, the two portions are regarded as parts of completely different networks in order to ensure the isolation and independence of both portions. The virtualization of network functions in a (generic) cloud environment, such as vertical network slicing, can be exploited to realize this scenario.

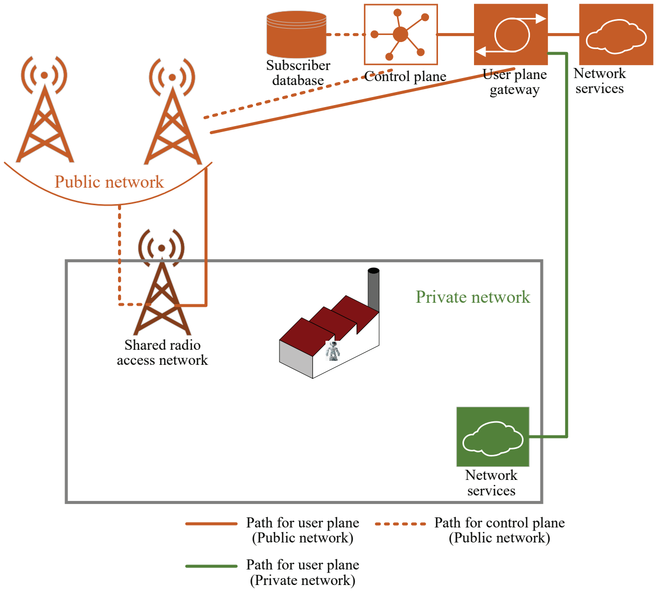

Fig. 4. Deployment in a public network. (Adapted from [18])

III. DEPLOYMENT AND IMPLEMENTATION CHOICES AND ISSUES

In this section, some implementation issues in private 5G networks are discussed.

A. Spectrum Opportunities

Obviously, the deployment of private 5G networks depends on the availability of spectrum. There are three spectrum options for non-public networks [26].

1) Licensed Spectrum: Licensed spectrum for private 5G networks can be obtained from mobile network operators, i.e., a mobile network operator allocates a dedicated portion of his owned spectrum bands for private use. This is a continuation of the classical spectrum licensing model, and different business models may apply.

2) Dedicated Private Spectrum: Dedicated private spectrum is obtained from the regulator. Due to reduced interference, non-public 5G networks operating with dedicated private spectrum provide great performance certainty. Moreover, this dedicated model enables the operation of private 5G networks independently from public mobile network operators. Therefore, it is being explored in many markets. For instance, the German government reserved a band of 100 MHz in 3.7-3.8 GHz for industrial use. The Japanese government allocated 200 MHz bandwidth in the 4.5 GHz band and 900 MHz bandwidth in the 28.2 GHz-28.3 GHz band to companies, enabling them to build their own 5G infrastructure. In the USA, the Federal Communications Commission (FCC) allows 3.5 GHz Citizen Broadband Radio Service (CBRS) to be used for private networks, by employing a spectrum sharing technique not to interfere with others already using such bands or nearby ones. Similarly, in China, the 3.3-3.4 GHz band can be used for indoor use cases, whereas the licensed 5.925-7.125 GHz band is targeted to industries [27].

3) Unlicensed Spectrum: Unlicensed spectrum has the potential to enable private networks to expand rapidly as spectrum is free of charge. Asynchronous and synchronized shared spectrum are two main spectrum sharing modes proposed for 5G in unlicensed spectrum, e.g., in the 2.4 GHz, 5 GHz bands, and the recently authorized 6 GHz band [28].

Asynchronous shared spectrum can be used in private 5G networks that do not require URLLC, and medium access is controlled through listen-before-talk sharing protocols. Synchronized shared spectrum, instead, enables more reliable performance than the asynchronous model, mostly in co-sited deployments, and its use is recommended in non-public networks requiring enhanced URLLC. Unlicensed spectrum schemes, however, pose concerns to some industries due to external interference and malicious jamming, which can result in service discontinuity. Note that malicious jamming is also problematic in the licensed spectrum. However, its economical advantages should not be disregarded.

Let us recall at this point that given that there are four deployment approaches and three spectrum options, private 5G networks may be realized in principle in twelve different forms, as shown in Table II. Particularly, in Table II, we compare the five most typical network forms in terms of customization, isolation, self-control, and costs.

B. Integration with TSN

The term TSN that originates from the name of a task group of the IEEE 802.1 working group [29], refers to a set of technologies and standards that aim at “guaranteed data transport with bounded latency, low delay variation, and extremely low loss” [30]. TSN was originally proposed on the basis of the standard Ethernet. However, wired connectivity increasingly fails to cater to the trend of Industry 4.0 in terms of mobility and flexibility, as discussed in the introduction. In [31], the authors investigated wireless TSN that employs a central controller to provide the IEEE 1588-based time synchronization, and the 802.1Qbv-based time-aware scheduling to address latency and reliability requirement. The physical layer was specified by the 802.11ax standard. Integrating TSN with private 5G is a promising solution to provide deterministic communication for real-time industrial applications [32], [33].

To support tightly time-synchronized nodes in TSN, IEEE 802.11AS [34], a subset of IEEE 1588 [35], is being used to provide fast time and frequency synchronization mechanisms between the grand-master node and the endpoint clock. Note that since 5G provides new services (e.g., high accuracy positioning services) and uses new technologies, (e.g., new architectures for backhaul and fronthaul, carrier aggregation, coordinated multipoint (CoMP), interference mitigation), which require a very accurate time synchronization, it can further benefit from TSN synchronization.

Importantly, 3GPP R16 started to specify the integration of 5G and TSN systems [36]. As shown in Fig. 5, the 5G system is integrated within the TSN network as a logical TSN bridge. TSN translators are responsible for the inter-working between the 5G system and the device side, and between the 5G system and the network side. The translators also map TSN configurations to the 5G QoS framework. In this manner, the 5G system functions act as a black box with respect to the TSN entities, and dispenses with the requirement of the TSN controllers for supporting protocols that are parts of the external TSN system.

The work on the 5G-TSN integration is still at an early stage and effective solutions are highly encouraged. For example, motivated by the observation that the 5G system bridge strongly impacts the integration, the authors in [37] quantified the 5G system bridge delay for a closed loop control application. Particularly, since private 5G networks are able to deploy the core network locally, data in the core network can experience considerably reduced delay.

C. Operation and Management

For a private 5G network, it should be specified who operates and manages what part of the network. Operation and management mainly involves the monitoring of the private network in real time and how much control and freedom the operational manager has [18]. For instance, the traffic QoS for critical applications can be monitored for safety management. One can manage the extent of the control and freedom of the private network operations, such as the ability to create, configure, and monitor dedicated non-public network functions.

There are two operation and management models: isolated and integrated [38]. For the isolated operation model, the

TABLE II
THE DEPLOYMENT AND SPECTRUM OPTIONS FOR PRIVATE 5G NETWORKS[†].

	Dedicated private spectrum	Licensed spectrum	Unlicensed spectrum
Stand-alone[‡]	–high customization –fully isolated in physical –high self-control –very high costs	—	—
Shared RAN	–high customization –fully isolated in logical –moderate self-control –high costs	–moderate customization –moderate isolation –moderate self-control –moderate costs	—
Shared RAN and control plane	—	–low customization –low isolation –low self-control –low costs	—
Hosted by the public network	—	–low customization –no physical isolation –low self-control –very low costs	—

[†] Depending on the operational model of the dedicated private spectrum for the private network, Table II can be summarized as follows. The stand-alone model enables high customization owing to a full physical isolation. Thus, accurate self-control is, in principle, possible, but it entails very high costs. The shared RAN model enables high customization owing to a full logical isolation. In contrast to the stand-alone model, moderate levels of self-control are possible at lower costs. With licensed spectrum, the shared RAN can moderate costs compared with that involving dedicated private spectrum owing to moderate customization. For the shared RAN and control plane model, licensed spectrum makes low customization, so that it limits low self-control at low costs. In particular, when licensed spectrum is hosted by the public network, only low self-control is possible because of the low customization. However, it benefits from low deployment costs.

[‡] As a particular case, a standalone network can be as customized as a shared RAN deployment. However, this table assumes a non-customized RAN deployment for a standalone network.

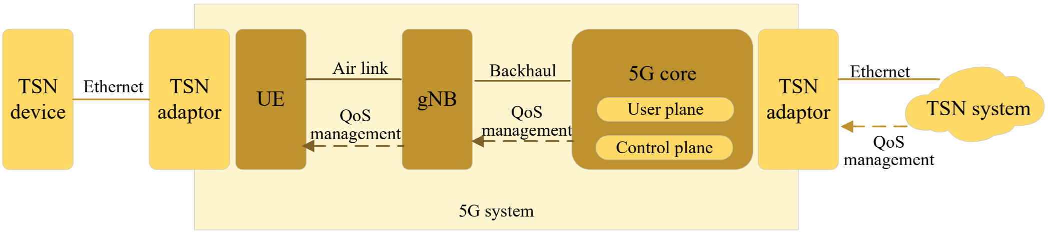

Fig. 5. The integration of 5G and TSN systems. (Adapted from [10])

operation and management of the non-public network is independent from that of any other networks. The owner can operate the network directly or outsource the operation to a third party. For the integrated operation model, the non-public network is operated and managed in combination with an external one (e.g., public mobile network operator). It is worth noting that the operation and deployment models can be realized independently to a great extent. This means that a stand-alone non-public network can be operated and managed in the isolated model.

IV. Key Enabling Technologies

In this section, we discuss some key enabling technologies for private 5G networks, including channel measurement and modeling, URLLC, network slicing, interference management, and localization and tracking.

A. URLLC

Private 5G networks are expected to provide URLLC, achieving a packet error rate of as low as 10^{-9}. It should be noted that this figure for the reliability makes sense and can be calculated only if it is related to a statistical model over which the URLLC system operates [39]. In general, the statistical model and the associated probability distribution of the parameters are unknown, and need to be learned by the URLLC system. Especially, the authors in [39] showed that channel uncertainty greatly impacts the URLLC system in guaranteeing high reliability. In addition to the fundamental statistical problem of guaranteeing high reliability, URLLC is based on a set of different enablers: [40]–[42].

1) Short Transmission Time Interval: Adopting fewer orthogonal frequency division multiplexing (OFDM) symbols per transmission time interval (TTI) and shortening the OFDM symbols via a wider subcarrier spacing reduces latency. In this direction, and compared with LTE where each TTI — the minimum unit that can be scheduled— comprises 14 OFDM symbols and last for 1 ms, 5G NR introduces the mini-slot concept, which may be comprised of 2/4/7 OFDM symbols, and allows TTIs as small as 0.125 ms [43]–[45]. Moreover, the latency required to achieved a given reliability decreases because with a shorter TTI, it takes less time to have enough hybrid automatic repeat request (HARQ) retransmissions for achieving a reliability target. Note that single-carrier transmission is also a promising solution for URLLC [46], considering that OFDM peak-to-average-power ratio and out of band emissions may degrade the system performance, eventually negatively affecting URLLC.

2) Spatial Diversity: Techniques harvesting spatial-diversity are believed to be able to simultaneously deliver low latency and high reliability [47]. Spatial diversity typically is realized by using multi-antenna transmission and reception. For transmit diversity, multiple antennas transmit the same data through different channels, while for receive diversity, multiple antennas receive different copies of the same signal over different channels. It was reported that URLLC devices should be equipped with at least 2×2 antennas [42]. Besides, spatial diversity can be attained via cooperation among distributed antennas, such in CoMP, without the need for large physical antenna arrays [33]. In order to achieve flexible spatial degrees of freedom and increase the spectral efficiency and coverage of the network, distributed antenna systems (DASs) are also promising for private networks [48], [49], as an extension of its usage in indoor communication systems [50], [51]. When each antenna operates as a BS, the DAS is working as the CoMP system. The key advantage of CoMP is to support simultaneous communications from multiple BSs to a single or multiple users over a whole communication region, with the resulting signal power enhancement and inter-cell interference reduction.

3) Grant-Free and Non-Orthogonal Multiple Access (NOMA): Grant acquisition and random access are two major sources of delay. For grant-based radio access, when a user has data to transmit, it should send a scheduling request (SR) via an SR-valid physical uplink control channel, which takes some time. Without the requirement for scheduling and granting processes, grant-free techniques are shown to be superior to grant-based transmission in terms of latency [52]. On the other hand, for orthogonal multiple access (OMA) techniques, contention-based random access may result in severe collisions and high latencies, especially for massive users. NOMA may be able to reduce latency through power or code domain multiplexing and support more users than conventional OMA in a grant-free manner for some scenarios [53].

4) BS Densification: BS densification contributes to URLLC in several ways. First, the BS-user association distance decreases with increasing the BS density. A shorter association distance means a lower propagation loss and higher desired signal power, increasing the signal-to-noise ratio or signal to interference plus noise ratio, if inter-cell interference is properly managed. Network densification also allows resource reuse, thus increasing resource allocation per user. This increment in resources can be directly utilized to reduce latency, or alternatively to enhance reliability, if interference is keep to a tolerable level. Finally, in dense network setups, BSs are likely to have a few or even no associated users within their coverage. Such user-void BSs can be exploited to provide extra associations for URLLC users by cooperating with neighboring BSs.

5) Device-to-Device (D2D) Communications: D2D communications enable physically close devices to communicate directly over a so-called sidelink, rather than following an uplink-downlink topology [54]. Compared with regular uplink-downlink communication, D2D communications experience shorter link distances and fewer hops. Therefore, D2D communications have great potential to provide low latency and high reliability, particularly with the new enhancements in the NR V2X domain.

B. Network Slicing

As discussed in Section II, network slicing is a key enabling technology for the deployment of public network integrated private 5G networks. Network slicing refers to a means of providing “a network within a network” by dividing a physical network into multiple logical ones, i.e., network slices, each of which is specialized to provide specific network capabilities and characteristics for a particular use case [55], [56]. Network function virtualization and software-defined networking are two core enabling technologies for network slicing. Network slicing architectures comprise three layers, namely infrastructure layer, network slice instance layer, and service instance layer. The life cycle of a network slice includes four phases: preparation, commissioning, operation, and decommissioning. Please refer to [57]–[59] for the latest surveys on network slicing in 5G.

Network slicing that customizes a shared network infrastructure [60] can be applied to intelligent transportation, smart homes, smart grid, Industry 4.0, etc. For example, the authors in [61] proposed to virtually divide the air-ground integrated vehicular network into three types of slices, i.e., high definition map for navigation slices, file of common interest slices, and on-demand transmission slices, in order to deal with the high management complexity caused by the heterogeneity in traffic and resources.

It should be noted that most studies on network slicing have focused on regular public networks, while little emphasis has been placed on slicing in a private 5G network. In [62], the authors presented a cross-domain network slicing solution to industrial applications with strict and flexible QoS requirements. The authors in [63], presented a network slicing management technique that can be used to implement, orchestrate, and manage network slicing in different deployments of a private 5G network. To guarantee physical isolation of the network and no interference between different domains, network resources are allocated by a time-division multiple access (TDMA)-fashion in [60]. In [56], the authors proposed the gateway-level RAN slicing. Indeed, private 5G networks are expected to serve multiple verticals with different service requirements. Thus, applying a vertical network slicing to private 5G networks will be of significant importance [56]. With network slicing, traffic can be segregated in an end-to-end manner. Network slicing also has the capability of isolating computing, storage, and networking resources. Hence, the physical infrastructure of a non-public 5G network is guaranteed to be shared efficiently among different applications.

As a practical example, it should be noted that the hierarchical RAN intelligence controller (RIC), which was introduced by O-RAN, a cloud-native software, includes AI capabilities to adapt the radio resource management operations [64], such as radio link management, mobility management, and admission control, so that the owner of the private network can readily slice the network according to its need.

C. Private Edge Computing

Edge computing is also an effective enabling technology for private 5G networks. Compared with traditional cloud computing, edge computing is a decentralized computational paradigm, in which the edge of the network has the capability of performing computationally-intensive tasks and storing a mass of data [65]. Due to the close proximity between user equipment and edge servers, edge computing can enhance location awareness, improve privacy security, relieve cloud storage, reduce energy consumption, and shorten response time [66]. It should be noted that edge computing and cloud computing can cooperate with each other. Specifically, based on the high computational and storage capabilities, cloud computing processes non-real-time big data, while edge computing performs real-time tasks and makes real-time decisions. Thus, a real-time analysis can be possible for the data generated by several end terminals [67].

Generally, the reference architecture of edge computing can be divided into three layers, namely device layer, edge layer, and cloud application layer [68]. The device layer includes various machines, sensors, and instruments, which transmits generated data to and receives instructions from the edge layer. The edge layer processes the data from the device layer, and may also forward data to the cloud application layer for further processing. Importantly, the edge layer provides time-sensitive services. The cloud application layer obtains and processes massive data from the edge layer, and then makes non-real-time decisions.

Private edge computing further enhances the advantages of the edge computing by adding secure and private services for local demands and network settings. That is, it provides agile content distribution and RAN-aware content optimization that rely on the local statistics. Relying on the local statistics, it is easy to build a Virtual Environment of Things (VEoT) [69] that merges IoT and AR. It also makes it possible to integrate emerging artificial intelligence (AI) for interactive monitoring, controlling, effective adaptation to dynamic wireless environments, and optimizing available resources. Further, combining collaborative and distributed AI via the private edge network, a large scale adaptation of private edges is promising in large-scale private networks that cover inter-domain connectivity [70]. Thus, the private edge facilitates distributed AI and cloud processing in 5G private networks via application programming interfaces (APIs). In contrast to conventional centralized cloud computing, the private edge is installed in a distributed fashion, so that it can reduce the possibility that a single attack could destroy the whole network. Thus, the private edge plays a key role in protecting the local area and sensitive information from digital attacks [71].

D. Interference Management

In an industrial environment, multiple signal transmission from controllers to actuators interfere with each other, which negatively affects the reliability and latency. Hence, interference management is very important for private 5G networks. In this subsection, we discuss four interference management techniques in IIoT.

1) Multiple Access: Multiple access is one important interference management techniques, which avoids the reuse of some radio resources by multiple nodes/users. WE may find deterministic and random approaches to multiple access. Time, frequency, code, and spatial division multiple access schemes are four typical deterministic multiple access techniques, in which different users are allotted to different time, frequency, code, and spatial resources, respectively, in a contention-free manner. By contrast, random-based multiple access schemes are contention-based channel access schemes, in which nodes should contest for the wireless channel with one another to send data. ALOHA and carrier sense multiple access are two popular random multiple access schemes. To avoid a queuing delay due to retransmissions and reduce the packet arrival delay, non-orthogonal HARQ was proposed in [72].

2) Spread Spectrum: Spread spectrum, typically including direct sequence (DSSS) and frequency-hopping spread spectrum (FHSS), can be used to combat interference. DSSS makes the transmitted signal wider in bandwidth than the information bandwidth. After the despreading at the receiver, the information bandwidth is restored, while the interference is substantially reduced. DSSS is the preferred option to combat low-medium narrow-band interference. By contrast, FHSS reduces likelihoods of colliding with other transmission via frequency-hopping, and is preferred for severe interference environments. Similar to spread spectrum, UWB communications convey information across a wide bandwidth without interfering with conventional narrowband transmission in the same frequency band.

3) Transmission Power Control: Transmission power control involves the dynamic adjustment of transmit power to reduce energy consumption, manage co-channel interference, and increase spectral efficiency, while ensuring successful communication and maintaining a given QoS. Transmission power control has been adopted in wideband code division multiple access, and included in the industrial wireless standards [73]. In [74], an adaptive multi-channel transmission power control algorithm was proposed for industrial wireless networks. In [75], the authors proposed an effective adaptive power control to avoid mutual interference between the primary and secondary networks in cognitive radio based IIoT.

4) RF-controlled Intelligent Reflecting Surface: An intelligent reflecting surface (IRS) [76], [77] consists of a large number of small, low-cost, and passive elements. IRSs have the following advantages: IRSs do not amplify or introduce noise when they are reflecting signals; IRSs can be intelligently mounted on existing infrastructure, such as walls and smart buildings; IRSs can be reconfigured to adapt to changes in the environment; and IRSs provide provides nearly line-of-sight (LoS) communication links. The primary functions of an IRS [76] are redirection (refraction and reflection) that steers to a completely custom direction, which generalizes the existing Snell's law; beam splitting that steers a wave towards multiple directions in parallel; wave absorption that minimizes reflected and refracted power for an impinging wave; and wavefront focusing that makes the IRS act as a lens to focus an electromagnetic wave to a given point. By controlling the phase-shift of reflective elements, the phase of reflecting signals can be dynamically controlled to cover a mobile transmitter, receiver, and the target object. In addition, by effectively combining the above four functions, interference can be reduced at the desired location.

E. Localization and Tracking

Many applications of private 5G networks that involve the interaction between the digital and physical world with situational real-time awareness, such as automated guided vehicles (AGVs), industrial autonomous mobile robots, healthcare, highly immersive VR and AR, asset tracking, and HMI, highly rely on accurate and timely location information [77]. Note that since a location estimate is based on measurements that rely on statistical signal processing, local statistics provided by the private network play an essential part in object localization and tracking.

Traditional Global Navigation Satellite Systems hardly provide accurate positioning, especially in indoor industrial environments [78]. Hence, RF-based localization is a crucial attribute of private 5G networks. Moreover, 5G New Radio (NR) has a number of characteristics, such as the use of multiple antennas and a wide bandwidth, which make accurate positioning possible. The fundamental RF-based positioning techniques can be categorized into:

1) Trilateration: The location of a mobile device in space is determined by using multiple distance measurements between the terminal and multiple spatially-separated known BSs. The measurements can be time of arrival (ToA), time difference of arrival (TDoA), and received signal strength. The authors in [79] considered ToA-based localization in 5G ultra-dense networks with randomly distributed nodes, and proposed three location estimators by using both the range measurements and the distribution of the nodes. In [80], the authors discussed several industrial-related deployment aspects that influence the location accuracy of ToA-based approaches, and described techniques for reducing their negative impacts.

2) Triangulation: In this method, angle-of-arrival (AoA) or direction-of-arrival (DoA) of the received signals is used to estimate the position by forming triangles to the point from known BSs. In [81], the azimuth AoA of the line-of-sight path between a device and multiple transmission-reception points (TRPs) is first estimated and tracked. AoA estimates at multiple TRPs are then loaded into an edge cloud to obtain timely position information through, e.g., an extended Kalman filter based approach.

3) Scene Analysis: A database of fingerprints, each of which is associated with a specific location, is constructed in advance. Positioning is realized by matching the live data with the prior fingerprints. In [82], the authors developed a solution to cooperative localization between an unmanned aerial vehicle (UAV) and a ground robot. The UAV first achieves self-localization by computing a dense 3-D environment. The dense map is simplified to a 2.5-D one, which is further transferred to the ground robot for collaboration. Based on the 2.5-D map, the ground robot estimates its pose through the alignment between the panoramic image with the 2.5-D map.

4) Hybrid: The previous localization techniques can be combined to enhance the overall performance. For example, in [83], a Bayesian augmentation technique, which can work with TDoA and AoA measurements, was proposed for UWB localization in IIoT applications.

In addition to these mentioned techniques, Wi-Fi-based indoor localization can use either channel state information (CSI) from the physical layer [84] or received signal strength indicator (RSSI) measurements from the MAC layer [85]. Thus, with more advanced Wi-Fi standards, fine grained grained CSI measurements and RSSI measurements will be available, which will eventually improve localization and tracking capability of the private network. In particular, the private network will benefit from the RF-controlled IRS since it can provide an additional LoS path [77] to moving objects in multipath rich local areas such as factories.

F. Softwarization and Standardization of White-box Hardware

The O-RAN Alliance [22] has set up 9 technical workgroups, working on new standards for open and intelligent RANs. In particular, Working Group 7, also now as the white-box working group is responsible for the complete hardware reference design of a high performance, spectral and energy efficient white box base station. So far, working group has published several specifications, including O-RAN Deployment Scenarios and Base Station Classes for White Box Hardware. Moreover, the O-RAN Alliance also has created the O-RAN Software Community, which is a Linux Foundation project supported and funded by O-RAN to lead the implementation of the O-RAN specifications in open source. This project aims, more specifically, at creating solutions that can be utilized to unify and accelerate the evolution and deployment of O-RAN. In this way, vendor-free, private-network-owner-centric, and flexible resource management solutions can be easily implemented to deliver end-to-end 5G benefits in the local area.

V. USE CASES

Private 5G networks are secure, fast, and easy-to-manage networks that can provide reliable voice or data services inside buildings or in remote areas. Numerous use cases across different sectors can be supported by these networks.

A. Manufacturing

The manufacturing vertical has the widest range of use cases [86]. In this subsection, we discuss some examples of use cases for manufacturing enabled by private 5G networks.

1) Production Line Flexibility: Production line flexibility can be greatly improved by private 5G networks. Production lines involve various control systems and field devices (sensors, actuators, robotics, etc.), where stringent connectivity is required between them. Although wired networks such as Ethernet can be used, it is very difficult and costly to install and reconfigure them. In some scenarios, fixed wire networking is even impractical. Private 5G networks provide new opportunities for production lines. By using 5G private networks, production lines can be reconfigured rapidly to deliver new products.

2) Machine to Machine Communications: Private 5G networks enable efficient and reliable machine to machine communications. Thanks to the high reliability and ultra-low latency, interconnected machines and sensors that are widely distributed across the manufacturing facility can work collaboratively to perform production tasks and run complex processes to achieve a common goal.

3) Automated Guided Vehicles: AGVs play a vital role in production line, warehousing, and dispatch areas. With the extremely high and reliable bandwidth offered by private 5G, real-time sensors coupled with powerful image and video processors can be mounted on and supported by AGVs. Hence, the functionality, efficiency, and availability of AGVs can be significantly enhanced.

4) Connected Workers: Workers responsible for machine operations, quality inspections, and facility maintenance can be connected with high bandwidth across the manufacturing campus. New applications supported by this connectivity include paperless shop floor, personal safety monitoring, and worker location tracking. AR and VR are advanced use cases in manufacturing, aiming to finish jobs faster, more accurately, and more safely. Moreover, with AR/VR, many new workers can be trained simultaneously and safely in a virtual format instead of the real world, thus lowering the training expenses. However, wired connections are often used in VR and AR today, which could potentially be hazardous in some manufacturing scenes. Private 5G provides new opportunities to improve the experience of AR/VR [87]. Relying on 5G modems, AR/VR devices are able to host some on-device processing and distribute heavier computing to edge computers located in the on-premise network. This will enable more sophisticated and photorealistic graphics that some manufacturing facilities require.

5) End-to-End Logistics: Private 5G enables intelligent logistics. Finished goods, parts, assemblies, and supplies across production facilities, the input/outgoing supply chains, and warehouses can be equipped with low-cost tracking devices. By using IoT and IIoT technologies, the location, status, and environment in warehousing, distributing, and circulation processing can be exploited for intelligent decision supporting systems to improve the level of logistics service and reduce logistics cost and resource consumption. Moreover, the availability of seamless interworking between public and non-public 5G networks contributes to national and even international logistics.

6) Multi-Client Serving Facilities: Thanks to network slicing, private 5G enables multi-client serving facilities that provide clients with "private" sub-networks delivered from a common 5G infrastructure. Production and warehousing facilities benefit from this use case.

B. Mines

Mines are typically located in remote areas and miners often work in the underground where public cellular networks are not always available. However, reliable communications are required both on and under the ground. Private LTE has been deployed in various mines across the world [88], [89]. To conduct mining operations with greater safety and automation, there is a need to use private 5G technologies in mines. On the other hand, the working condition in the underground mines poses a significant safety risk to miners. Private 5G networks enable effective communication between surface and underground. Moreover, wireless sensor networks built on non-public 5G can be deployed in mines for monitoring the working environment, sensing mine disaster signals, and making early warning. When mining accidents happen, mining companies can quickly and accurately position the underground miners via the wireless sensor networks, facilitating the rescue.

C. Ports

Future ports face some challenges regarding equipment downtime, congested port yards for loading and unloading, worker safety, and environmental impacts. Private 5G enabled smart ports are expected to be promising solutions [90]. Four use cases with the most beneficial applications for smart port technologies are given in the following.

1) Remote-Controlled and Automated Cranes: Ship-to-shore cranes are used to load and unload container ships between the ship and the dock, while gantry cranes stack containers at terminals. Private 5G enables remote-control and automation with high precision and good maneuverability for these cranes.

2) AGVs: Using smart 3D sensors, AGVs regularly patrol the port to handle all port materials, reduce energy costs, and decrease risk of accidents.

3) Condition Monitoring: Condition monitoring systems can be set up to detect faults before they occur, reduce unplanned downtime, and maximize asset productivity. In addition, by predicting the lifetime of IIoT devices in the manufacturing chain, it can improve productivity by reducing the replacing time of the faulty devices.

4) UAVs: Private 5G aided UAVs benefit the port in a variety of ways. For example, UAVs can be used to deliver documents [91], [92] between the ship and the shore, surveil the security of the port, and enlarge the network coverage [93], where the UAVs can work as the relaying nodes to forward the information to non-functional areas. Furthermore, as a mobile edge computing (MEC), UAVs can play an important role in MEC services [94], [95]. Since the UAV networks can work with other existing private networks, it should be very robust and stable for small and large-scale operations.

D. Airports

In airports, private 5G can help control pandemic risks, optimize ground operations, and improve passenger experience. With the aid of 5G networks, automatic fever detection, facial recognition, and access to passengers' travel records can be facilitated to detect critical cases. Preventive measures empowered by 5G networks include monitoring social distance and employing AGVs for full disinfection. Being able to tackle process bottlenecks in ground operations, 5G is also a critical digital lever for punctuality and operational excellence. Besides, 5G triggers a new wave of digitization and innovation in airports that improve customer experience. For instance, 5G + AI-based boarding technologies accelerate check-in, luggage drop-off, identity checks, etc, shortening passenger waiting time. In addition, by an application of continuous security checks, the safety of the passengers can be improved. By resorting to 5G, AI-assisted computer vision can promptly identify and inform the owner of a lost luggage, guide passengers to right boarding gates quickly, and detect capacity issues for hand luggage before boarding.

E. Utilities

Utilities require secure, flexible, reliable, and broadband wireless connectivity to deploy new applications for improving grid safety and reliability, lowering operating costs, and providing better customer engagement. Smart meters, air conditioners, hot water heaters, etc., can be connected such that customers have real-time information on the power use. By using a private 5G network, power companies can deploy drones that carry imaging devices to visually inspect transmission lines. The safety and efficiency of field workers, especially in remote rural areas, underground locations, and tunnels, where commercial networks are not available, can be improved with private 5G based mobile applications such as push-to-talk/video. Moreover, utilities benefit from cyber security that private 5G networks can offer, protecting the critical infrastructures, such as the power grid from malicious actors.

F. Railways

Both overground and underground trains require critical communication services for train scheduling and smooth operations. For example, there is a need for secure critical voice communications between drivers and signaling controllers. Passengers on the trains also expect reliable and stable voice/data services. However, trains often run in the underground, tunnel, and remote areas, and unlikely gain access to public networks. Moreover, high-speed trains have a more stringent latency requirement. Enjoying high availability, high reliability, low latency, and customized QoS, private 5G provides an attractive solution to railway networks.

G. Media

The media industry benefits from private 5G networks in terms of both production and distribution. On the production side, remote production can be enabled. Real-time multi-camera feeds, including 4K ultra high definition (HD) content from the field can be sent over the networks to the production facility, avoiding an OB unit at the scene. Multiple production staff from different locations can work remotely and collaboratively on the same live content. Moreover, private 5G makes it possible to build a wireless studio, where all audio/video devices and equipment are connected over 5G. On the distribution side, by distributing live and non-live HD content to consumer via 5G, users can watch more content at high quality and without buffering.

H. Healthcare

Private 5G will transform healthcare in various ways. For example, it is able to get rid of wires and transmit large data files of medical imagery quickly and reliably to a specialist for review. A high-speed 5G wireless network expands the telemedicine market. Patients at home and doctors at hospitals can hold consultations via 5G-enabled video conferences. By using IoT devices, patients' physical signs and condition can be gathered and transmitted in real-time, facilitating quick healthcare decisions made by doctors. In healthcare, AI can be used for disease recognition and treatment determination. Private 5G networks can support the real-time rapid learning which requires a large amount of data. Besides, 5G-enabled AR/VR makes it possible to train medical students to perform surgical procedures in a virtual environment.

VI. DEMONSTRATIONS

In this subsection, we present some examples of real demonstrations for private 5G networks throughout the world.

A. Success Story of Ericsson in Factories

Ericsson deployed a 5G smart factory in Lewisville, Texas, USA [96]. The factory was identified by the World Economic Forum as a pioneer of Industry 4.0. By using the fast and secure 5G connectivity, 25 different use cases were developed. Typical use cases include energy monitoring and management, AR for remote support, and machine learning based visual inspection. In energy monitoring and management, all energy appliances are monitored for tracking, thus enabling the acquisition of real-time energy consumption information and the ability to turn on/off appliances. In AR for remote support, the factory maintenance team can be given virtual guidance from experts around the world to troubleshoot and repair equipment. In machine learning (ML) based visual inspection, by using high-resolution camera and ML algorithms, the accuracy of the inspection is increased and the time needed is reduced. Compared with a traditional factory, the 5G smart factory with more than 200 robots in operations is featured by 120% improved output per employee and 65% reduction in manual material handling.

B. Success Story of Huawei in Mines

China Mobile, Yangquan Coal Group, and Huawei successfully built China's lowest underground 5G network at Xinyuan

Coal Mine in Shanxi province [97]. The private 5G network is located as deep as 534 meters underground and achieves an upload speed of more than 1000 Mbps. Based on the 5G network, a 5G smart coal mine was launched and three 5G-enabled unmanned applications were developed to inspect electromechanical chambers, operations on the coalface, and comprehensive mechanized coal mining operations. These applications lower labor intensity and improve workers' security.

C. Success Story of Nokia in Ports

Nokia collaborated with the Hamburg Port Authority (HPA) and Deutsche Telekom on a successful 5G field trial at the Port of Hamburg in Hamburg, Germany [98]. Two single-antenna BSs are deployed with carrier at 700 MHz and connected to both the near and far data centers. User cases requiring strict and moderate latency rely on the near and far data centers, respectively. URLLC, enhanced mobile broadband (eMBB), and massive machine type communication (mMTC) are supported by the same 5G radio infrastructure through network slicing. The traffic light control is a typical application of URLLC. By monitoring and controlling the traffic lights remotely from the HPA control center, vehicles can be steered quickly and safely through the port. With eMBB, AR/VR is available to on-site engineering teams, so that they can access to up-to-date key information such as construction plans and resort to remote experts for technical support. IoT sensors enabled by mMTC are mounted on fixed and movable assets to consistently monitor the environment, and asset status and healthiness.

D. Success Story of Cisco in Warehouse

The US Department of Defense developed a smart warehouse at the Marine Corps Logistics Base in Albany, Georgia, using a private 5G wireless network with the technical assistance of Cisco and other technology companies [99]. The private 5G wireless network uses CBRS and millimeter wave spectrum. The framework triggers plenty of smart use cases, including robotics, barcode scanning, holographic, and AR/VR. These applications modernize operations and increase efficiencies in storage, inventory control, maintenance, and auditing.

E. Success Story of Mitsubishi Electric Corporation in Factory Automation

Mitsubishi Electric Corporation has verified wireless transmission between local 5G base stations and Mitsubishi Electric's FA products such as human-machine interfaces (HMI), edge computers, and programmable controllers [100]. In the demonstration, it used the 28.2-28.3 GHz spectrum which is assigned by the Japanese government. Its use cases include remote operation and maintenance support, and use of AR and VR for enhanced work efficiency.

F. Other Success Stories

Other success demonstrations are available from [56], [101], and [102]. In particular, in [56], the authors successfully demonstrated operation in 5G-NR non-standalone mode (30 kHz subcarrier spacing and 80 MHz bandwidth) utilizing the gateway-level slicing in the shared licensed spectrum, 3.8-4.2 GHz.

In general, industrial systems require guidance control techniques that demand sophisticated sensing and localization capability. Thus, the authors in [101] demonstrated real-time wireless closed-loop control of mobile platforms for future industrial system composed of collaborative robotics and AGVs that transport goods in a warehouse or moving containers in a port terminal.

In [102], the authors proposed an ultra-high speed indoor communication network using a novel cross spectrum and cross medium of optical fiber, millimeter-wave (mmWave), and optical wireless communications. It can support applications that require ultra high-speed and low-latency communications in local areas. Some potential use cases include ultra high-definition images of medical treatments in hospitals and cooperative robotics for smart manufacturing.

VII. POTENTIAL CHALLENGES AND FUTURE DIRECTIONS

Private 5G network is still in its infancy. There are still many potential challenges and open problems for private 5G networks that deserve further study.

A. Channel Measurement and Modeling

Understanding the wireless channel characteristics is a key factor in advance of the design, deployment, and testing of new wireless networks. Since non-public 5G networks are often deployed in industrial fields, we focus on the channel measurement and modeling for industrial environments in this subsection.

Due to structural (e.g., ceiling height) and environmental (e.g., surface material) differences, industrial channels' behaviors significantly differ from those in usual indoor scenarios such as office or home environments [103], [104]. Importantly, as the operating carrier frequency increases, smaller machine parts can act as good reflectors of electromagnetic energy. Thus, the path-loss exponents may be even less than two. In addition, since reflection, diffraction, and scattering of magnetic fields are prone to occur, industrial indoor channels are usually multipath-rich fading channels [105], [106]. Moreover, since wireless technologies did not play a critical role in industrial settings, less attention has been traditionally paid to channel measurement and modeling in industrial sites compared with urban outdoor/indoor environments. The limited related work in this field includes [107], which investigated several industry-like measurement scenarios over sub-6 GHz, and characterized large and small scale parameters as well as delay statistics of the wireless channels. Similarly, the National Institute of Standards and Technology conducted extensive measurements and evaluations, providing the channel statistics and propagation characteristics over 2.25 GHz and 5.4 GHz frequencies at industrial sites [108]. In [109], the wireless machine-to-machine communications of industrial robots at 5.85 GHz was considered. In [110], the authors published a raw measurement data set, which characterizes the time-and frequency- variant channel attenuation at 2.4 GHz in the presence of an industrial cyclic moving robot arm obstacle. The authors in [111] launched a campaign for the channel measurement in industrial environments associated with mmWave communications, and analyzed the statistical properties of the channel parameters using the mmWave channel model of IEEE 802.11 ad. In [112], a path loss and root mean square delay spread estimation algorithm was proposed via the room electromagnetic theory. References [113] and [114] complementary presented the results of channel measurement for industrial ultra-wideband (UWB) communications.

B. Spectrum Agile and Robust Use

The co-existence between Wi-Fi and cellular technologies is a topic that has received significant attention from regulators, vendors, operators, service providers, and the research community. The CSMA used in IEEE 802.11 has been widely adopted and specified as the channel access mechanism for cellular technologies, such as LAA and NR-U, although some minor differences still remain. Having both technologies using the same channel access method enables a large degree of co-existence.

As discussed earlier, some private 5G networks may use unlicensed spectrum, and in such cases, particularly when multiple of them use the same unlicensed bands, realizing massive IoT connectivity over such unlicensed bands requires efficient and reliable spectrum sharing and channel access among IoT and IIoT devices. The role of spectrum sharing has become key in spectrum management, allowing access to new bands, while protecting their operations and the access rights of incumbents or those of multiple different use cases, with distinct priorities. However, satisfying predictable and guaranteed QoS levels in unlicensed spectrum is a challenging problem, and up to which extent unlicensed spectrum can support URLLC is still unknown. Thus, to improve URLLC capabilities, it is necessary to design new spectrum sharing and channel access schemes that allow an agile and dynamic use of the large number of unlicensed channels in the 5 and 6 GHz spectrum. We envision a system where a given node may reselect a different channel in each transmission opportunity, thus reducing the channel access time in an opportunistic manner. IEEE 802.11be multi-band/multi-channel techniques are evolving in this direction. Moreover, such schemes should be able to access and prioritize, according to the service needs, the access to licensed spectrum in case such resource would be available. Thus, spectrum sharing will provide additional spectrum options to support innovation and enable new use cases in the private network such as control, resilient and reliable low latency wireless automation, extensive IoT and IIoT, and secured network within premises [56], [115].

C. Multi-Band Aggregation and Multi-Channel Operations

To increase the peak data rate and system throughput of a wireless system, it is necessary to employ a transceiver that transmits and receives signals to and from a private network by aggregating a plurality of bands that are available in unlicensed and licensed spectrum under the constraint of bounded latency. However, due to possible limited and discontinuous bands by unlicensed and licensed spectrum in the private network, new smart schemes for band aggregation are necessary. When many different types of devices are connected simultaneously, interference from other adjacent devices is the key impairment that degrades performance. In particular, device-dependent interference will be a unique impairment in the public network. Thus, it is necessary to develop device-dependent multi-channel operations, assisted by signal processing, to improve the performance of the private network by minimizing the inefficiencies due to interference [116]. In achieving multi-band aggregation and multi-channel operations, it is necessary not to exclusively use 5G and cellular radio interfaces. Thus, the integration of non-5G and even non-cellular radio interfaces in private networks is also an important research topic due to limited available spectrum [115].

D. Cyber Threats

Though the name may suggest private 5G networks are “private” and thus secure, they remain vulnerable to attack. This is because the wireless connection itself is on the airwaves and reachable by anyone within range. Since a private 5G network tends to be deployed in remote and hard-to-access parts of the world, and becomes the only point of contact with the outside world. In this case, there is a considerable risk of interception and misdirection by hackers. Another type of man-in-the-middle attack is through sending harmful signals that can drain devices batteries rapidly. These attacks have serious, even life-threatening consequences especially for those networks with mission critical IoT and IIoT devices. Besides, there may be a mobile network mapping attack that the types of devices connected to the network are determined by identifying data sent over cellular signals via wireless data-sniffing devices. It enables attackers access to sensitive information about the devices within a non-public network. Thus, scalability, control, and isolation in next-generation networks (SCION) will be one candidate to ensure trusted traffic across interconnected network architectures [70].

E. Fronthaul and Backhaul

For a successful industrial IoT operation, it is expected that private 5G networks will require enhanced capacity and URLLC to deliver flawless QoS. Furthermore, dense heterogeneous networks will be emerging in private networks. To satisfy these requirements and handle new type of networks, a highly reliable and flexible backhaul will be indispensable in realizing private 5G networks. Due to these high heterogeneity, QoS requirements, and node density (of APs and users), efficient joint forwarding/backhaul and access operations are required to achieve cost-effective transmission [117]. Existing backhaul solutions have not been fully developed, and are subject to high cost, unreliability or insufficient bandwidth [48]. How to better integrate backhaul intelligently, adaptively and dynamically, and make full use of the heterogeneity of the backhaul network to meet the diversity of user needs is a challenge. It turns out that prequel is a key element that has strict requirements for future networks, but at present, few new interfaces for pre-transmission are developed. The novel front-haul design is also worthy of research.

F. Control-Centric Radio Resource Allocation

Private 5G networks are aimed at meeting the need for critical wireless communications for industrial operations, public safety, and critical infrastructure connectivity. Most of these applications are control-centric rather than human-centric [17], [118]. Conventional resource allocation techniques that are designed for human-centric applications may not suitable for control-centric functions. Furthermore, the resource allocations for uplink and downlink are treated independently in conventional networks, which may not applicable any more to control-centric applications such as industrial automation.

G. Data Sharing

In private 5G networks, distributed data owners may need to share their data for implementing collaborative tasks. For example, environmental monitoring can be enhanced by combining data from multiple sensors distributed across the defined premises. However, data leakage may occur during data sharing, which may result in security and privacy issues. How to efficiently enable data sharing while preserving privacy is challenging. To provide intelligence on operations of collaborative tasks, the conventional ML techniques assume that data is available at the central server. However, due to transfer of the owners' data to a centralized third party server for training, there is possibility of privacy leakage. As one promising solution to reduce the leakage of privacy, a federated learning (FL) [119], [120] can be used as one of the distributed ML approaches. Especially, for wearable healthcare, a framework of the FL was employed in [121]. For privacy-preserved data sharing in IIoT, FL was employed by [122]. Further integrating the differential privacy [123], which is preventing the server from identifying who is a particular update, into FL, an enhanced privacy can be achieved.

H. Integrated Sensing and Communication

As we mentioned before, smart industry requires a variety of guidance control techniques that rely on sophisticated sensing integrated into communications capability [101]. Thus, industrial private networks will benefit from integrated sensing and communication (ISAC) [124] that achieves integration gain resulted from a dense deployment of a variety of sensors, and coordination gain resulted from balanced functional performance or/and mutual assistance. By integrating ISAC, extended coverage, higher reliability against failures, faster response, and more accurate sensing can be achieved. In particular, typical applications of ISAC are in industries that rely on ubiquitous IoT devices for guidance for closed-loop control, autonomous vehicles for logistics, wearable electronics for HMI, and Wi-Fi to drones for a delivery in large-scaled warehouses. Thus, how to integrate ISAC into 5G networks and emerging next version of Wi-Fi transparently and effectively is an open problem.

I. Device Ecosystem and Public-Private Continuity

During the initial 5G deployment stage, the device ecosystem is a challenge for private 5G. The range of commercially available 5G devices is not rich enough, although they are now undergoing rapid development. The issue of spectrum support also needs to be considered for 5G devices. Most announced 5G devices are understood to support services operating in sub-6 GHz spectrum bands, while many fewer devices are identified as supporting mmWave spectrum, and even fewer, both mmWave and sub-6 GHz bands. Some components needed for the development of new fully 5G devices, such as chipsets, require significant amounts of time and capital expenditure to roll out. In private 5G, mobility remains a key requirement, which means service continuity matters. Users may need to move from private to public networks and vice versa. How to provide continued services as they traverse these domains is challenging, which involves many factors to consider, such as QoS, security, and management.

VIII. CONCLUDING REMARKS

With the evolution of Industry 4.0, enterprises, utilities, and the public sector have strong interest in deploying private 5G networks to develop their own industrial applications for achieving superior operational efficiency and productivity. The global private 5G network market size is expected to witness compounded annual growth rate of 39.7% from 2021 to 2028.

This paper has reviewed the recent research on private 5G networks. Specifically, we first have introduced the basic concept and architecture of private 5G networks, and discussed several implementation issues. Next, we have analyzed some key enabling technologies for private 5G networks and introduced their industrial use cases and real demonstrations. Finally, we have identified the potential challenges and future directions.

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