Industrial IoT in 5G-and-Beyond Networks: Vision, Architecture, and Design Trends

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***Abstract*—Cellular networks are envisioned to be a cornerstone in future industrial IoT (IIoT) wireless connectivity in terms of fulfilling the industrial-grade coverage, capacity, robustness, and timeliness requirements. This vision has led to the design of verticals-centric service-based architecture of 5G radio access and core networks. The design incorporates the capabilities to include 5G-AI-Edge ecosystem for computing, intelligence, and flexible deployment and integration options (e.g., centralized and distributed, physical and virtual) while eliminating the privacy/security concerns of mission-critical systems. In this paper, driven by the industrial interest in enabling large-scale wireless IIoT deployments for operational agility, flexible, and cost-efficient production, we present the state-of-the-art 5G architecture, transformative technologies, and recent design trends, which we also selectively supplemented with new results. We also identify several research challenges in these promising design trends that beyond-5G systems must overcome to support rapidly unfolding transition in creating value-centric industrial wireless networks.**

***Index Terms*—5G-and-beyond, Industry 4.0, IIoT, open RAN, private 5G, mmWave-MIMO capacity, NR-U, TSN, Security.**

I. INTRODUCTION

In unlocking the hallmark capabilities of Industry 4.0 in various industries (e.g., automation, manufacturing, utilities), the role of the fifth-generation (5G) networks in providing full-scale wireless connectivity and coverage is unquestionable [1]. The full-scale connectivity is a prerequisite to all-inclusive capturing of data streams from (static or mobile) systems, machines, and sensors for real-time monitoring and control by edge controllers as well as updating IT-management systems for planning and predictive maintenance. The data collection and utilization, befitting to industrial needs, open possibilities in creating value in the manufacturing processes in terms of their responsiveness to the demands, efficiency, capacity utilization, and product/service innovation [2]. However, the industrial systems are (time and mission) critical, with stringent communication availability, reliability, latency, and security requirements (see [3, Table 1]). Thus far, primarily inflexible real-time Ethernet extensions and sparingly, for localized and low-mobility applications, wireless technologies (e.g., WirelessHART, ISA100, WiFi) are utilized [4]. Meanwhile, employing wireless in vertical industries is not without many concerns, for instance, i) ensuring industrial-grade robust connectivity and fail-safe operation ii) satisfying the diverse and heterogeneous connectivity requirements, iii) integration with existing industrial networks, and iii) managing/operating wireless networks without compromising security and privacy, etc. To overcome all such concerns, 3GPP is unraveling the 5G's service-oriented architecture design. Nonetheless, the new research trends are striving to design context-aware and value-centric beyond-5G networks through verticals-technology joint design [5].

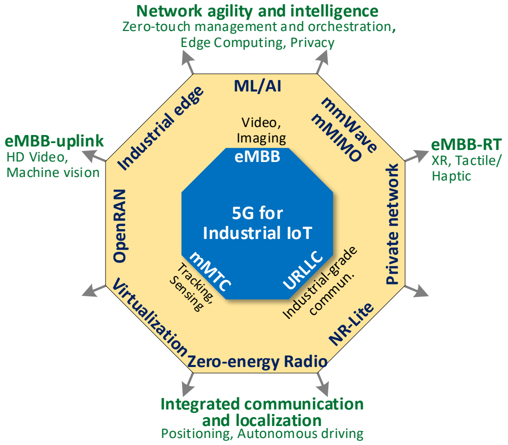

Fig. 1. Beyond-5G vision, 5G architecture and design trends for IIoT.

Objectives. *This article presents the vision, architecture, and state-of-the-art design trends of 5G-and-beyond networks for industrial IoT (IIoT), as defined below and illustrated in Fig. 1.* The earlier related works have either presented IIoT requirements and challenges [4] or summarized the 5G's design and evolution for Industry 4.0 use-cases [6], [7]. Meanwhile, other recent studies have speculated the vision, uses-cases, key performance indicators (KPIs), and enabling technologies of 6G systems [8]–[11], including artificial intelligence (AI) for ubiquitous computing and network management [12], [13]. On the contrary, this article provides a comprehensive study of designing and optimizing 5G-and-beyond networks to address the earlier mentioned concerns of vertical industries.

In this respect, after defining the vision for enhanced wireless for IIoT, this study describes the industrial-centric features in 5G's service-based architecture and integration with industrial Ethernet. It also discusses the core transformative technologies in beyond-5G networks to fulfill capacity, positioning, and distributed computing demands in future IIoT. Further, it presents emerging design trends and the

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associated research challenges, including various constructs of network deployment models (e.g., agile and intelligent design, operation, and management) and spectrum access for private networks, green communication-computing paradigms, and integration of heterogeneous IIoT networks. Unique to this study are the novel supporting results on millimeter wave (mmWave) channel capacity under the 3GPP indoor factory channel [14] and dynamic network slicing in IIoT networks with intelligent slicing policy. Finally, it outlines the security and privacy concerns and enhancements in the emerging wireless-AI-edge ecosystem and private networks.

Vision. Industry 4.0's digitization drive targets removing any barriers in relaying all-inclusive sensory information of mobile/static assets for monitoring, control, and predictive maintenance. Across industries, the communication requirements vary from massive, broadband, and critical IIoT. In addition, many future data-intensive IIoT services require real-time (uplink) broadband and integrated communication and localization services for pervasive edge intelligence, imaging, augmented/virtual reality (XR), tactile Internet, and haptic control applications. To support these services, wireless industrial Internet is expected to provide wide-scale and fine-grained coverage and context-aware connectivity, with machine learning (ML)/AI-driven flexible network orchestration and management, edge intelligence and computing, and privacy according to future industrial needs [8], e.g., dynamic production [15]. *The rest of this article introduces architecture and design trends in 5G-and-beyond networks to meet this vision.*

Architecture. To address the connectivity demands in industrial verticals, 3GPP laid the foundation of 5G radio access network (RAN) and core network (Core) architecture in Release-15 with high-capacity enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable and low-latency communications (URLLC) services. These basic services can be exploited to support diverse and heterogeneous IIoT use-cases with 5G's unified connectivity solution. Meanwhile, the 5G Core introduces time-sensitive networking (TSN)-integration, flexible deployment options with physical or virtual resources, mobile edge computing (MEC) to empower the factory owners or service providers to tailor the industrial Internet to the desired performance targets. *We discuss 5G's architecture and its various features for different IIoT connectivity segments in Sec. III.*

Design Trends. Under the vision of futuristic IIoT services, the design and development of beyond-5G networks has started unfolding towards: i) transformative technologies, including: integrated 'high-capacity communication' and 'cm-level positioning' over mmWave together with massive multiple-input multiple-output (mMIMO) for data-intensive and location-aware applications; intelligent and data-driven edge/cloud computing schemes for creating autonomous IIoT networks, ii) vendor-independent software-based open RAN architectures for intelligent resource allocation/slicing and function virtualization, and customizable private deployment/spectrum options, enabling service providers and enterprises to manage their networks, iii) targeting new vertical markets with WiFi-like 5G-enabled access in unlicensed bands and NR-Lite for reduced-capability devices, and lastly iv) all these new deployment options open up many new security and privacy challenges/concerns for industrial Internet. *We discuss these emerging design trends and associated research challenges in beyond-5G networks in Sec. IV & V.*

II. WHY NEXT-GENERATION WIRELESS NETWORKS FOR INDUSTRIAL IOT

This section gives a brief background on existing industrial wired/wireless communication networks and describes 5G's role in providing enhanced IIoT connectivity.

A. Industrial Connectivity: A Brief Background

In many industrial sectors (e.g., utilities, mining, industrial automation), real-time automation uses wired communication networks, commonly based on real-time extensions of IEEE 802.3 Ethernet [16]. The extensions are often incompatible with the standard Ethernet, and the convergence with enterprise IT networks is challenging, albeit much needed for realizing Industry 4.0 vision. Recently, IEEE 802.1 TSN, an open set of standards, is emerging to provide truly converged networks for both the deterministic and best-effort traffic over Ethernet. On the other hand, the existing wireless technologies expressly designed for industrial communication include [17]:

- ISA100.11a and WirelessHART standards for process automation, which are IEEE 802.15.4-based for short-range mesh connectivity.
- IO-Link Wireless[1] for wireless networking, over Bluetooth, between sensors, actuators, and controllers in the factory automation control systems. IO-Link Wireless is an extension of the IO-Link IEC 61131-9 standard.
- Industrial wireless LAN (IWLAN) by Siemens, which is currently in use for factory automation, automotive, transportation, etc.

The incentives in using these standards are energy-efficiency and operation in unlicensed frequency bands. Otherwise, their scope is limited to low-rate or localized IIoT applications with low mobility. Conversely, recent low-power wide-area network (LWPAN) technologies such as LoRa, Sigfox, and 4G narrowband (NB)-IoT (see Sec. III-A for its evolution in 5G) are useful to support low-mobility applications over wider areas [18]. Meanwhile, the recent WiFi 6 (IEEE 801.11ax) is also targeting low-latency applications in enterprises [19]. However, industrial use-cases present an extreme variation in requirements, ranging from low-cost but energy efficient to high mobility and robust connectivity at any cost, wherein 5G-and-beyond cellular networks with various radio advancements, unified connectivity and coverage, and dedicated spectrum hold advantage over other fragmented solutions.

B. 5G for Enhanced Industrial Wireless

The wireless ecosystem of emerging cellular networks, which were optimized for coverage/data rates until 4G, has been extended to supporting small data from a massive number of connected devices and delivering quality-of-service (QoS)-aware connectivity. Since 3GPP Rel-15[2], this utility shift has

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[1] www.io-link.com/ilwse

[2] The timeline of 3GPP Releases for 5G NR evolution is given in Fig. 2

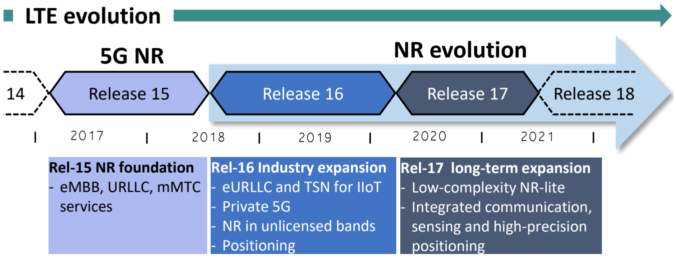

Fig. 2. Timeline and key features of 3GPP Releases

been a driving force in the design of 5G-and-beyond networks as compared to earlier cellular systems. For uplink-dominant monitoring and bidirectional (monitoring and control) traffic, mMTC and URLLC respectively are finding wider traction, especially from vertical industries wanting to digitalize their systems. The key factors making 5G-based industrial wireless attractive, as a drop-in replacement or complementing industrial networks, are as follows.

Unified connectivity and dedicated coverage. 5G's unified wireless interface for eMBB, URLLC, and mMTC services, and broad RF spectrum portfolio, can support both outdoor and indoor service and coverage demands of industrial communication. Further, the private 5G deployment options can give complete control to customize IIoT networks, without involving mobile network operators (MNOs) [3].

Mobility and collaboration. 5G offers built-in support for handling mobile things (e.g., automated guided vehicles, robots, mobile controllers) and their collaboration.

Integrated communication and sensing. With new spectrum allocation beyond-6GHz, massive MIMO and beamforming technologies, 5G has the capacity to support AR/VR, HD video, imaging, and cm-level positioning to enable real-time situation awareness applications in indoor industrial settings.

III. BREADTH AND DEPTH OF IIOT IN 5G ARCHITECTURE

The 5G design and evolution give the needed breadth and depth to address a multitude of use-cases across multiple industries and even allow multiple IoT segments to coexist to serve a single vertical industry, e.g., factory automation. Industrial wireless demands can broadly be grouped into three IoT segments: massive, broadband, and critical. This section provides an overview of the 5G services and selected features tailored for meeting industrial-specific demands within each segment, as summarized in Fig. 3.

A. *Massive IoT*

Massive IoT (mIoT) targets massive number of connected low- to medium-end industrial devices (meters, sensors, trackers), mostly battery-operated, and sending/receiving a small volume of sensory information (e.g., temperature, humidity, position location). Although mIoT devices' demands on latency and reliability are non-critical, supporting extreme device densities (up to $10^6/\text{km}^2$) in various industries (e.g., manufacturing, utilities, automotive, logistics) is needed [20].

In 3GPP LTE framework, LTE-M and NB-IoT were introduced as mIoT solutions in Rel-13. LTE-M supports low-complexity Cat-M class devices for machine-type communications, while NB-IoT is a standalone protocol stack, built on LTE's design, for reduced-capability radio access. Although LTE-M/NB-IoT fulfill the 5G's IMT-2020 targets for mMTC, many industrial wireless sensor network (WSN) use-cases (e.g., video monitoring, wearables, battery-constrained devices) are still not best-served by 5G eMBB, URLLC, and mMTC services. A new 3GPP study item has initiated new radio (NR)-based solution—*NR-Lite*—for reduced capability devices. The other motivations for NR-lite are: enabling co-existence with URLLC, utilizing higher 5G frequency bands, and taking advantage of other 5G features like network slicing.

Concerning the evolution of mIoT solutions in 5G architecture, 3GPP defines a dual-mode cloud core comprising 5G evolved packet core (EPC) and 5G Core (5GC), where (existing or future) LTE-M/NB-IoT devices can connect to 5G EPC [21]. 3GPP also provides an option to serve Rel-16 compatible Cat-M/NB-IoT devices in 5GC. Since 5G NR frequency allocation includes new and old 4G bands, where LTE, LTE-M, and NB-IoT devices are operational, the dynamic spectrum sharing feature in 5G allows disruption-free coexistence between 4G and 5G networks.

B. *Broadband IoT*

Broadband IoT extends high data rate (i.e., eMBB) services to data-intensive IIoT use-cases. Compared to traditional eMBB, data-intensive use-cases have different requirements and traffic patterns. Therefore, broadband IoT targets providing additional IoT-related features such as low latency and enhanced battery-saving, coverage, and uplink data rates. 5G NR will offer data rates in tens of gigabits per second (Gbps) through higher-order modulations, multi-antenna transmissions, carrier aggregation, uplink-driven dynamic time-division duplex (TDD), and the introduction of 5G NR in the new and old spectrum. The new mmWave frequency bands with a wider bandwidth will also enable NR to provide a network-based accurate device positioning [22].

C. *Critical IoT*

Critical IoT is for time-critical industrial use-cases, with a demanding requirement-set of latency and reliability, e.g., ITU has set a minimum latency target of 1-ms with a 0.001% packet error rate [23]. It covers use-cases such as collaboration and control of machines, robots and processes, mobile robots, real-time human-machine interaction (HMI), automated guided vehicles, autonomous cars, and AR/VR applications. These use-cases are relevant to the manufacturing, logistics, automotive, mining, and utility sectors. 5G NR introduces several enabling URLLC features to support critical data flows, grouped into *low latency* and *ultra reliable* communications.

1) *Low-latency communications*

The most notable low-latency communications (LLC) options are described below.

Adjustable TTIs. 5G NR introduces adjustable resource granularity through variable TTIs (transmission time intervals) duration to achieve low latency. Adjustable TTIs enable fast and flexible scheduling; URLLC traffic can even be scheduled at mini-slot level (as short as a fifth of a regular slot).

Fast processing. As traditional hybrid repeat request (HARQ)-based retransmissions of unsuccessful transmissions are not affordable for URLLC traffic, NR enables fast HARQ by

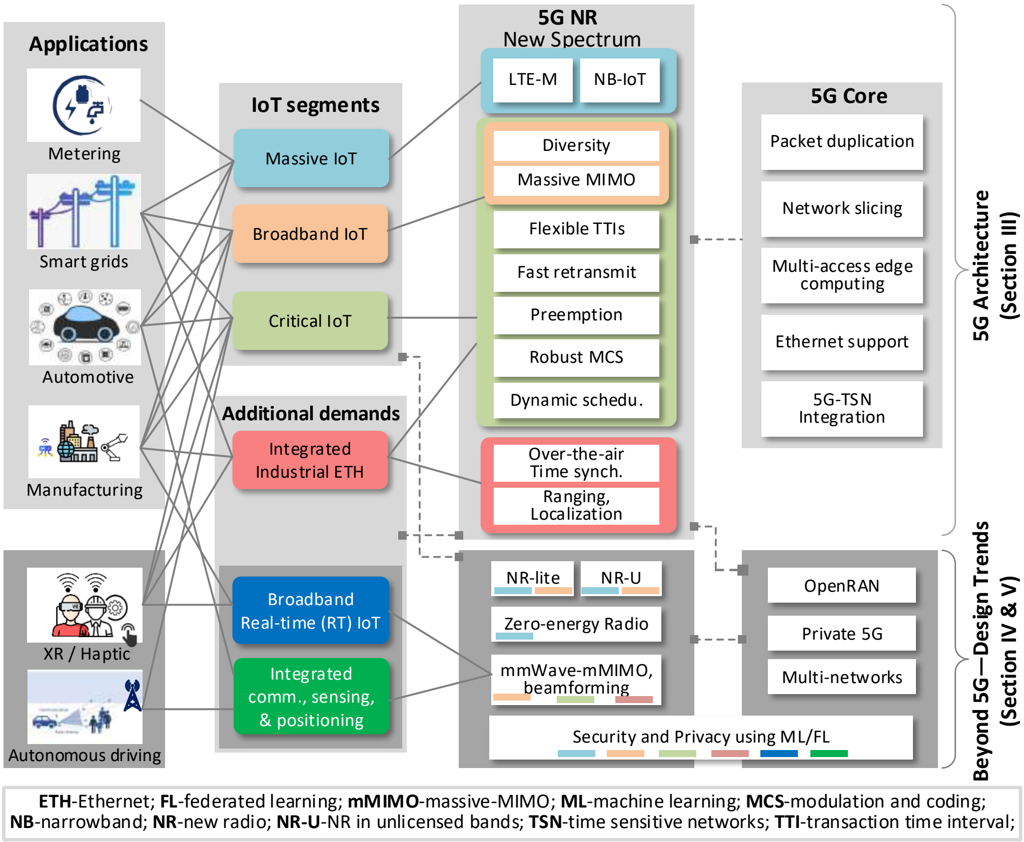

Fig. 3. 5G NR and 5G Core service-oriented architecture and features to serve different Industrial IoT segments. The design trends in expanding the 5G architecture towards beyond-5G networks for industrial vision shown in the lower part.

speeding up a user equipment (UE)'s processing to decode a downlink transmission and prepare a new uplink.

Preemption. Preemption provides priority-based radio access to URLLC traffic when coexisting with eMBB traffic. NR introduces inter-UE UL/DL preemption, wherein a URLLC packet can preempt an ongoing eMBB transmission. To minimize the impact of DL preemption on eMBB traffic, the base station (BS) can indicate the preempted part of the transmission, and the users can employ smart recovery schemes to recover the affected code block groups [24].

2) *Ultra-reliability*

A selected list of 5G reliability-enhancing features are:

Ultra-robust modulation and coding. For typical wireless traffic, link adaptation schemes have relaxed error rate targets, i.e., 10%–30%. However, to support extremely low error targets in URLLC, NR requires robust modulation and coding schemes (MCS) for the data and control channels, which comes at the cost of spectral efficiency. As control channels carry critical information to configure communication parameters, they require extra robustness; however, grant-free (GF) transmission schemes can avoid this extra degree of uncertainty [25].

Diversity. Various diversity schemes, such as multi-antenna techniques, the use of multiple carriers, and packet duplication at PHY/MAC, are a crucial element of URLLC reliability toolbox [26]. Moreover, in a dynamic mobile environment, macro-diversity is a suitable solution in which path redundancy is achieved with multiple BSs serving a single UE. Coordinated multipoint (CoMP) is one such technique under cloud-RAN architecture to perform non-coherent or coherent joint transmission to the same UE.

Medium access/scheduling. Compared to 4G's proportional fair scheduling to provide fair data rates to users, the design of URLLC packet scheduling policies needs to consider the time-sensitive nature of URLLC traffic. NR introduces *semi-persistent scheduling* (SPS) and *configured grant* (CG) scheme. SPS supports periodic transmission flows of UEs, where resource blocks, MCS and schedule start time is indicated by the BS. As supporting 1-ms latency target in UL is infeasible using handshake schemes, *CG* or scheme allows a BS to periodically configure UL transmission parameters, and a UE having data can transmit immediately on the pre-configured resources. With its basic features defined NR Rel-15, such GF access is imperative for uplink URLLC. However, beyond-5G networks will require reliability and scalability improvements in massive GF transmissions for which advanced schemes, such as dynamic retransmission, non-orthogonal multiple access (NOMA), and coded-random access [27], need to be designed.

3) *Core Network Features*

The IIoT-centric core network (CN) features by 3GPP are outlined below.

Packet duplication. Industrial Ethernet networks provide fault tolerance against packet failures and latency violations, e.g., using parallel redundancy protocol (PRP) [28]. PRP concurrently transmits a data packet over two independent paths. Meanwhile, NR also introduced packet (PDCP-PDU) duplication in Rel-16 to realize PRP-like functionality. PDCP duplication is supported for both the user plane and control plane paths, where 5G allows establishing redundant paths through the 5G systems (5GS), including RAN, CN and transport network [29].

Network slicing. It enables MNOs to create virtual networks over a common network; a slice comprises a dedicated or shared subset of network functions and resources (processing power, storage, bandwidth) to provide negotiated QoS to a customer. Network slicing aims at supporting diverse service classes (e.g., eMBB, URLLC) over a common physical network; the slices can operate concurrently while maintaining isolation as per guaranteed service level agreement with vertical industries. Slicing can span across a 5G system including access, transport, cloud, core networks, or even multiple operators. Additionally, as a part of the network slice, edge computing can provide the physical infrastructure to realize network functions (NFs) [30] as software instances for IIoT.

Multi-access edge computing. Enables low-latency computations and storage environment at the edge—close to the data source—of a network. By edge processing, mobile edge computing (MEC) reduces the application traffic, enhances user data privacy, and improves the service performance of applications (e.g., AR/VR, distributed control) requiring low-latency and real-time control. MEC can enable numerous value-added services, such as data analytics, location-based services, ML/AI, and data caching. The MEC standards (covering frameworks, architectures, and use-cases) are handled by ETSI ISG MEC (Industry Specification Group for MEC) [31], while the support for MEC is specified in 3GPP SA2.

D. 5G Add-ons for Industrial Ethernet

The integration of 5G-and-beyond networks with the existing/emerging industrial communication networks (i.e., real-time Ethernet and TSN) hinges upon additional features to achieve flexibility and full-scale digitization. 3GPP has standardized industrial features, e.g., Ethernet support, Ethernet header compression, TSN integration [32]. 5G includes support for both the base-bridging features and the TSN add-ons.

5G-TSN integration. 3GPP Rel-16 supports a centralized configuration model for 5G-TSN integration, wherein a TSN central network controller (CNC) configures and schedules TSN flows through 5GS. The 5GS acts as a transparent bridge by introducing user and control plane TSN translators (TTs). The TTs translate/adapt the flow control, QoS, and time synchronization between TSN and 5GS while masking 5GS's internal working and exposing only the necessary capabilities to TSN-CNC (see [32] for further details). In 5G-TSN integration, the 5G CN features have an essential role (e.g., for TSN traffic isolation and duplication); still, TSN traffic handling in 5GS will require resource management solutions to map it to a needed QoS profile.

Time synchronization. Time synchronization is deeply embedded into 5GS (radio/core entities), while it is extended to device-level for time-critical applications in Rel-16 [33]. Meanwhile, TSN nodes synchronize with a master clock using IEEE 802.1AS generalized PTP (gPTP) protocol [34]. The 5GS-TSN translators can either support the gPTP message's forwarding or use 5GS's internal clock as a grandmaster. In either case, estimating the sojourn time of synchronization messages in the 5GS is critical to achieving precise time synchronization of TSN nodes. The critical component in 5GS is the errors in the over-the-air distribution of reference time due to uncertainties in propagation delay estimation in multipath propagation environments [23]. Therefore, further study on designing advanced propagation delay estimation techniques (e.g., carrier phase estimation-based) is needed to achieve ultra-tight accuracy of $< 1\mu$s.

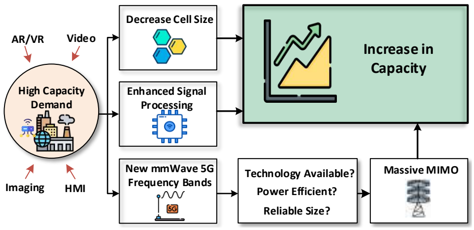

Fig. 4. Three main techniques to increase capacity that are attractive for data-intensive IIoT use-cases.

IV. TRANSFORMATIVE TECHNOLOGIES FOR FUTURE IIOT

5G-based industrial Internet needs to provide reliable wireless access for connecting both the stationary (monitoring sensors, smart-cameras) and mobile (controllers, robots) devices with the distributed local/remote industrial data centers [35]. In such scenarios, the exchange of large volume of manufacturing data wirelessly demands high capacity (up to 40 Gbps for stationary and 5 Gbps for mobile devices) while simultaneously sustaining cm-level positioning accuracy of industrial devices in harsh multipath conditions [36]. Meanwhile, the collected time-series big data must be processed at the edge and/or cloud layers using advanced ML/AI techniques for intelligent automation. In this respect, various enabling techniques, i.e., advanced signal processing methods, variable cell size, new frequency spectrum (c.f., Fig. 4), and new trends in edge/cloud computing, are being explored in 5G-and-beyond networks for meeting diverse IIoT needs.

A. High Capacity and Positioning Services

1) Reducing Cell Size and Enhanced Signal Processing

The ongoing exponential rise in cellular services has led to extensive research in advanced signal processing methods, i.e., 5G NR flexible and scalable physical layer, non-orthogonal multiple access (NOMA), and multi-tier heterogeneous cell deployment (picocell and femtocell) strategies [37], [38]. The aim is to enhance spectrum efficiency while meeting high-traffic demands. The reduction in cell size, support for new mixed numerology, carrier aggregation, and asynchronous services in 5G RAN can provide massive connectivity and reliability to IIoTs [39]. However, the throughput remains limited since the existing sub-6GHz spectrum is insufficient for meeting extreme bandwidth/throughput demands of data-intensive IIoT use-cases. As a result, the need for a shift beyond sub-6GHz frequency bands is imminent for IIoT.

2) mmWave Bands, massive-MIMO, and Beamforming

Using millimeter-Wave (mmWave) RF technology and mMIMO, together with the new unexplored spectrum (c.f. Sec.V-A2), can lead to a tenfold increase in the achievable capacities; thus, supporting IIoT-based futuristic factory deployments [35]. Therefore, the beyond-5G mmWave-based IIoT systems can benefit from underutilized mmWave spectrum, without significant interference concerns due to the LoS nature of mmWave communication. However, a significant constraint is the higher path losses inside the factory environments because of shorter wavelengths (1mm-10mm) [40]. On the positive side, millimeter-wavelength enables the close placement of massive antenna elements in the same physical space, forming mmWave-mMIMO antenna arrays [41].

The mmWave-mMIMO array elements provide directional gain (through beamforming) to combat higher path loss. The current trending design of partially-connected hybrid-mMIMO array architecture has groups of antenna elements combined to form subarrays, with each subarray having dedicated RF chains. Also, induction of modern on-chip antennas for mmWave-mMIMO array design proves to be cost-effective and power-efficient, enabling compact radio design of mmWave transceivers for IIoT devices [42]. Currently, 1024 and 64 antenna elements, while 32 and 8 RF chains are under consideration by 3GPP at gNodeB (gNB) and user-devices, respectively.

To study the realistic effects of path losses, beamforming, and site-specific propagation characteristics, physical MIMO channel models are needed, for which 3D statistical channel models (SCM) are gaining popularity [43]. As an example study, we created a mMIMO channel matrix, $\mathbf{H} \in \mathbb{C}^{N_{\text{Tx}} \times N_{\text{Rx}}}$ based on channel statistics of the indoor factory (InF) conditions by following the 3GPP SCM framework [14, Sec. 7]. Note that N_{Tx} and N_{Rx} are the maximum number of mMIMO sub-arrays at gNB and industrial device, respectively, and each sub-array has 64 3GPP antenna element models. Fig. 5 shows the maximum information capacity C (Gbps/Hz) using (1) of an InF link with respect to signal-to-noise ratio (SNR).

$$C = B \cdot \log_2 \left[\det \left(\mathbf{I}_{N_{\text{Tx}}} + \frac{\Omega_{\text{T}}}{N_{\text{Tx}} N_0} \mathbf{H}\mathbf{H}^{\text{H}} \right) \right], \qquad (1)$$

where $\mathbf{I}_{N_{\text{Tx}}}$ is the identity matrix of dimension $N_{\text{Tx}} \times N_{\text{Tx}}$, N_0 is the system noise, Ω_{T} is the total transmit power (equally divided among SAs), $(\cdot)^{\text{H}}$ denotes Hermitian transpose, and B is the system bandwidth. From Fig. 5, it is observed that increasing the subarrays configurations and average SNR at the mmWave-based mMIMO system can deliver a multi-fold increase in the link capacities even in harsh InF channel conditions, which will be crucial to support the communication requirements of future real-time broadband IIoT services.

3) Precise Positioning over mmWave Spectrum

A variety of emerging applications in automated factories require positioning of machines, robots, and automated guided vehicles (AGVs) within centimeter-level accuracy, e.g., for geofencing. A commonly used global positing system (GPS) can provide an accuracy of 5 m; however, it fails in indoor obstructed environments as it gets reflected and attenuated. Autonomous vehicles utilize LIDAR (light detection and ranging) technology to relatively estimate distances with other traffic at sub-millimeter accuracy [44]. Other positioning solutions based on ultra-wideband (UWB), RFID, Bluetooth, and WiFi round-trip time (RTT) are also being developed, where UWB with the bandwidth of 500 MHz (in 3.1 GHz–10.6 GHz band) in particular can achieve higher ranging accuracy [45].

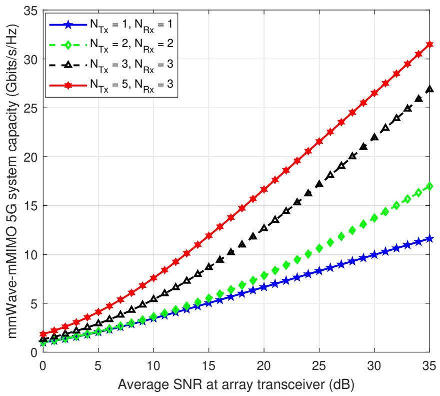

Fig. 5. Realistic mmWave indoor factory (InF)-link capacity using partially-connected hybrid mMIMO architecture for different transmitter (gNB) and receiver (industrial device) sub-array configurations for $B = 1$ GHz.

In contrast, 5G-and-beyond systems with large mmWave spectrum and precise beamforming antenna technology can provide centimeter-level of accuracy together with user tracking, ML/AI, exploiting multipath signatures, and device-to-device (D2D) cooperative localization techniques [22]. The attractiveness in using mmWave is to use the same network infrastructure for communication and localization jointly. Two promising research directions for localization with massive antenna array and model-based neural networks in mmWave system are discussed in [46].

B. Distributed Edge/Cloud Computing

The IIoT system consists of a wide range of heterogeneous IIoT devices connected through heterogeneous wired and wireless networks, such as WSNs, WiFi, and mobile (4G/5G) networks [47]. As a result, the distributed IIoT devices form an edge computing network to collect and pre-process real-time industrial data and transmit it to the remote cloud data centers for industrial computing/control operations, such as remote equipment monitoring, predictive maintenance, and quality control. The IIoT devices are growing rapidly, and their massive data transmission and processing cannot be supported by traditional cloud data centers within requirements of industrial applications [48]. The raw transmission of IIoT data to the cloud also incurs significant network resource consumption and creates a bottleneck at the wireless/wired backhaul. Therefore, offloading some data streams from cloud to edge computing networks is an essential solution, especially for time-sensitive industrial tasks. As a result, edge computing networks' trend shifts toward a multi-technology convergence integrating advanced network technologies such as software-defined networks (SDN), network function virtualization (NFV), and 5G networks.

Nevertheless, the centralized cloud-based systems are still necessary for supporting the IIoT applications for their abundance in computational, storage, and communication resources. Therefore, the IIoT-edge-cloud ecosystem has become prevalent for different IIoT applications where computational-intensive offloading is critical. Edge computing helps the IIoT applications to offload QoS-aware computational tasks of IIoT devices to the nearby edge servers via single-hop communication. However, with the advent of big data in IIoT control and management applications, the IIoT devices require an IIoT-edge-cloud ecosystem for striking a trade-off between latency sensitivity and computational efficiency in a multi-hop communication setting. In this case, the cross-layer optimization of cooperative computation offloading [49] and load-balancing [50] within the IIoT-edge-cloud ecosystem facilitates the abundant computational and storage resources of the cloud layer where the real-time edge analytic and data-prepossessing for the IIoT devices are performed at the edge layer. Furthermore, such an ecosystem paves the way for the native deployment of the ML/AI-based IIoT control and management applications in beyond-5G networks [51], with non-real-time model training and real-time control at the cloud and edge, respectively. Towards energy-efficient and real-time inference on edge devices, the recent results [52] on learning model size reduction with accurate nanosecond inference are encouraging for realizing this vision for IIoTs.

V. DESIGN TRENDS AND RESEARCH CHALLENGES

The baseline 5G architecture is expanding rapidly to novel application domains and new use-cases. However, designing 5G-and-beyond network architecture for IIoT requires a holistic take, including a) the ability to tailor the connectivity infrastructure, using intelligent network automation, service orchestration, and integration, according to the current and future needs of distributed and modular industrial systems, and b) the opportunities to exploit the industrial data and incorporate cybersecurity by design. In this respect, the transformative technologies of the previous section, together with emerging technological trends, will shape the future IIoT networks in several aspects ranging from network architecture and deployment models (open and intelligent RAN, private 5G, network slicing, sustainable and heterogeneous networks), and spectrum access and coexistence models (licensed, unlicensed, mmWave bands). This section presents a discussion on these design trends and the new security and privacy dimensions for IIoT in 5G-and-beyond networks.

A. *Network Deployments*

1) *OpenRAN*

The envisioned open RAN ecosystem aims to enable an *open and intelligent RAN* environment through standardized network elements and interfaces. Such open RAN ecosystem formation creates synergy between projects, alliances, and working groups (WGs) with different futuristic use-cases. For instance, in 2017, the Telecom Infra Project (TIP) launched a project group OpenRAN [53], which aimed to define and build 2G to 4G RAN solutions for general purpose and (vendor-independent) hardware and software-defined technology. Consequently, the OpenRAN project group devised a plan toward analyzing and developing potential use-cases and fronthaul algorithms to achieve the objective. Meanwhile, in 2018, a new consortium of network operators, namely the O-RAN Alliance, started working with the open RAN architecture and deploying options for evolving RAN, leveraging ML/AI to support real-time and non-real-time network management and control.

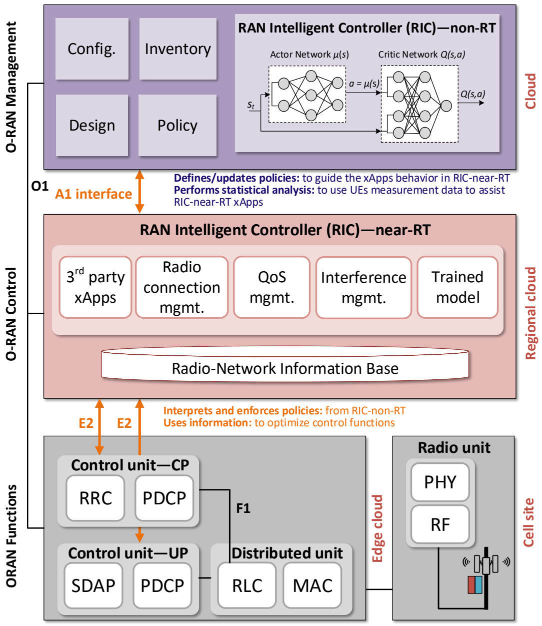

Fig. 6. Modular design of O-RAN control and management layers, and its integration with 5G Core. Definitions: RRC–radio resource control, RLC–radio link control, MAC–mediun access control, CP–control place, UP–user plane, PHY–physical layer, SDAP–service data adaptation protocol, PDCP–packet data convergence protocol.

Currently, O-RAN Alliance has eight active WGs to achieve several technical objectives, such as open fronthaul design for next-generation virtualized RAN, RAN cloudification, ML/AI-driven RAN management and control, and software specification for NR protocol stack. In this case, the TIP has been contributing to Stack Reference Design Workgroup (i.e., WG8) of the O-RAN Alliance, to develop the software architecture, design, and release plan for the O-RAN control unit (CU) and O-RAN distributed unit (DU) based on O-RAN and 3GPP NR specifications. However, the TIP OpenRAN does not aim to define new open RAN interfaces or specifications instead accelerating adoption and deployments.

In Fig. 6, the control unit (CU) and distributed unit (DU) functions are virtualized to enable the baseband processing that operates over the commercial off-the-shelf (COTS) servers under the O-RAN architecture. Such CU/DU virtualized functions operate either at the cell-site/near-edge (i.e., near the RRH) or the regional cloud [54]. As a result, the service providers greatly benefit from such O-RAN architecture where disaggregated hardware and software provide highly scalable network customization depending on their demands and available network infrastructures. Among eight possible 5G functional split options [55], the 3GPP defined two 5G-NR split architectures that meet the fronthaul requirements in the O-RAN. As shown in Fig. 6, option 7 (or 7.2) provides a low-level split suitable for URLLC and near-edge deployment. Additionally, the O-RAN architecture introduced two main modules as the radio intelligent controllers (RICs), which are the near real-time RIC (near-RT RIC) in the O-RAN control and non-real-time RIC (non-RT RIC). The non-RT RIC and near-RT RIC enhance the traditional network functions with embedded intelligence where the near-RT RIC is interfaced with the CU-CP and CU-UP. The CU-CP is responsible for signaling and configuration messages and data transmission, whereas the DU access the CU to provide services for end-users through the RRH air interface. Apart from these, to configure and manage the decomposed RAN architecture programmatically, O-RAN employs the Internet Engineering Task force's (IETF's) NETCONF/YANG (Yet Another Next Generation) standard [56]. The YANG [57] is a modeling language that defines the syntax, relationships, and constraints to model the configuration and operational state of the O-RAN managed functions through remote procedure calls (RPCs). The challenges of network management and operation for the IIoT environment under O-RAN differ from traditional RAN solutions in several critical aspects.

Operation and management. The remote factory management system requires on-time and updated environmental data collection from IIoT devices to enforce up-to-date control decisions in safety-critical applications. However, the transmission path between the IIoT devices and nearby BS or gateway can be obstructed by physical objects causing multipath fading and signal attenuation, along with increased interference from unintended sources. Consequently, intelligent O-RAN radio connection/interference/QoS management critical industrial services can significantly enhance the KPIs for the future IIoT networks. Within the O-RAN architectural design, the intelligent O-RAN operation and management (O&M) enforces policy-based resource management at near real-time RAN Intelligent Controller (*RIC near-RT*) functions (on a timescale of < 1s) to achieve the desired IIoT performance gains. Furthermore, in a real-time industrial monitoring and control environment, sub-optimal ML/AI hyper-parameter optimization in the *RIC non-RT* may lead to poor RIC near-RT industrial O&M decisions.

Planning and design. The IIoT radio resource management (RRM) solutions are becoming more data-driven than the existing model-driven approaches under the existing virtual RAN (vRAN) and cloud RAN (C-RAN), paving the way towards intelligent network management solutions. In this respect, the envisioned O-RAN planning and design for the IIoT should enhance the legacy RRM while leveraging the next generation RRM with embedded intelligence. Unlike the static RAN resource management solutions, the O-RAN in the IIoT environment must ensure reliable orchestration of third-party industrial applications or xApps[3] with the near-RT RIC control loops that are highly responsive. Importantly, such data-driven and automated IIoT network resource management for the IIoT services must capture the dynamics of the industrial communication channel realistically.

2) Private 5G Networks

5G private networks, also referred to as non-public networks (NPNs) by 3GPP, are physical or virtual 5G cellular systems deployed for private use by entities, such as enterprises, to provide dedicated wireless connectivity. With critical IoT and industrial automation IoT features of 5G architecture, NPNs can offer deterministic service to industrial use-cases while giving complete control over every aspect (privacy, security customization, management, control) of the network. The security and privacy aspect of NPNs are discussed in Sec. V-G. There exist four deployment models for 5G NPNs [3], as shown in Fig. 7, with increasing level of integration between public and private networks while confining the data flows within the enterprise's premises.

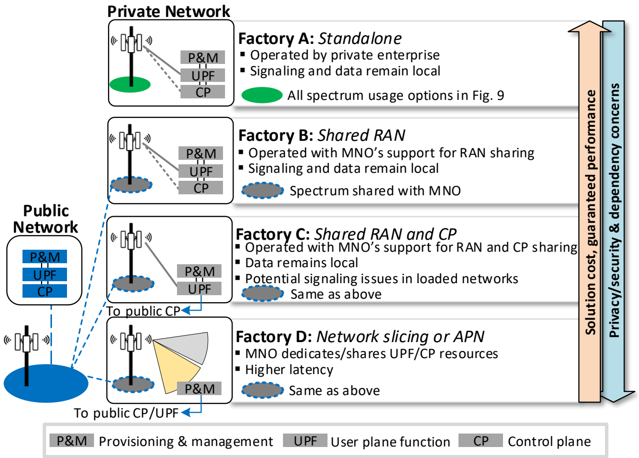

Fig. 7. Private factory 5G deployment options, distribution of functional elements and integration with a public network, and pros. and cons.

- In *standalone private deployment*, the private network is completely independent of the public network.
- In the *public–private shared RAN deployment*, the private network shares the RAN with the public network, while maintaining independent network functionalities.
- In the *public–private shared RAN and control plane deployment*, the private network shares both RAN and control plane functionalities with the public network.
- The *network slicing* model provides dedicated or shared subset of network resources to private industries with a service level agreement assurance.

By design, these models provide flexibility to tailor private networks to individual needs on security, safety, and resilience. However, enterprises will need innovative autonomous solutions, especially in sharing-based models, for real-time monitoring of QoS and service availability and management (e.g., configuration, troubleshooting) of shared network resources and functions for delivering an extreme range of IIoT requirements and maintaining fail-safe operations. Therefore, these models require a radical change in the way the network/service is managed and orchestrated, wherein AI/ML-based network automation and predictive maintenance solutions can be investigated. Some practical solutions/guidelines for such automated design for private 5G have already started; for instance, AI-driven automated end-to-end network slicing [59] and MEC-base system to exploit SDN/NFV functions in the wireless edge [60]. Moreover, the spectrum usage options must coincide with NPNs' reliability and coverage requirements.

Spectrum Options for Private 5G. Spectrum allocation is critical for the success of private 5G-and-beyond networks, especially for demanding IIoT applications. For supporting the large number of use cases and delivering high capacity and wide area coverage, regulators have allocated spectrum to 5G in the high (e.g., mmWave), mid (e.g., 1-10 GHz), and low (e.g., sub-1GHz) frequency bands. Meanwhile, the technical and commercial choices, depending on the spectrum

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[3] xApps can be deployed by IIoT stakeholders (e.g., network/factory operator) to include new features in B5G-based control applications. For example, intelligent traffic steering driven by native AI/ML across different layers and RAN technologies to improve spectral efficiency and network capacity [58].

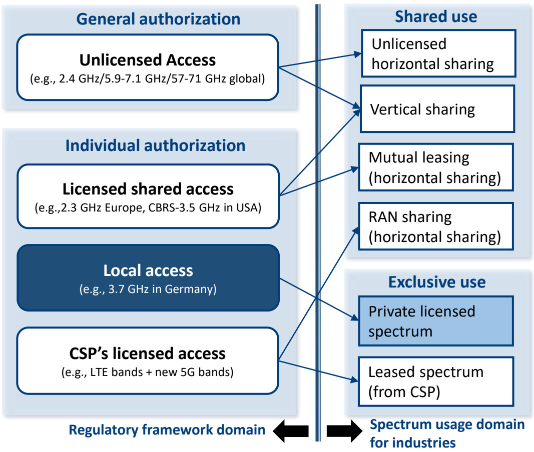

Fig. 8. Spectrum usage options for private networks with respect to spectrum regularity models giving localized, exclusive, and shared usage options.

licensing policy of the concerned national spectrum authority, for spectrum access include:

- **Licensed spectrum**: cellular spectrum is commonly offered through an open award process to MNOs on a nationwide basis.
- **Leased spectrum**: spectrum subleasing from MNOs is an alternative option for businesses planning to operate their industrial 5G.
- **Spectrum reservation:** there is an ongoing regulatory discussion on reserving nationally/internationally harmonized cellular spectrum (e.g., 3.7 GHz in Europe) for private local 5G networks.
- **Shared spectrum**: is another option to operate a private 5G, where the businesses require light-licensing, and the same band users need to coordinate, e.g., CBRS 3.5 GHz shared spectrum in the US.
- **Unlicensed spectrum:** the unlicensed bands (e.g., 2.4 GHz, 5 GHz, and 60 GHz) are open to everyone, requiring to (intelligently) coordinate with other users.

Fig. 8 shows a portfolio of spectrum usage options for private networks. The increasing variety of spectrum bands, with different propagation characteristics and spectrum access options, results in many new challenges for 5G-and-beyond networks. For enterprises looking for cost-effective, fast deployment, shared and unlicensed spectrum access are attractive, but meeting demanding QoS requires new enablers for interference/coexistence mitigation; for instance, database technologies for interference coordination [61] and AI/ML inspired algorithms for on-device interference detection/classification [62] to data fusion for constructing dynamic interference maps [63].

B. Network Slicing for Multiservice Coexistence

To satisfy the diverse QoS requirements of industrial use-cases over a common physical network, it is essential to transform the IIoT networks into software-based intelligent network slicing solutions [30], operating on general-built physical network infrastructures [64]. Network slicing, for multiservice coexistence in IIoT networks, has received significant attention in recent years [65]. In this regard, compared to vRAN and C-RAN, O-RAN opens new possibilities for network slicing, offering a flexible and cost-effective multi-vendor network infrastructure to MNOs [66].

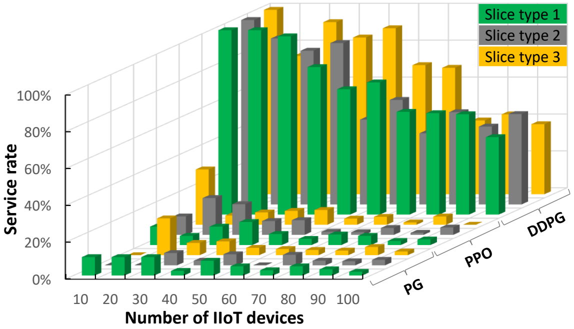

Fig. 9. Comparing service rates of different slice types w.r.t IIoT devices while employing DDPG, PPO, and PG-based slicing approaches. The number of BSs is fixed at 5. Slice types are in the decreasing order of QoS demands, with type 1–emergency traffic, type 2–scale reading, and type 3–mobile robotics.

Slicing allocates resources on the RAN (among others, as computing, storage) to each service while ensuring mutual isolation through orthogonal or non-orthogonal resource allocation (e.g., preemption and NOMA). For example, for coexisting eMBB and URLLC, an orthogonal downlink resource slicing services in 5G networks is studied in [67] while a deep reinforcement learning (DRL) solution is proposed for downlink non-orthogonal slicing in [68]. Meanwhile, the performance trade-off in uplink multiplexing of URLLC and eMBB services over orthogonal and non-orthogonal multiple access is analyzed in a multi-cell C-RAN scenario in [69]. Since energy efficiency is important in harsh industrial settings, the authors in [70] formulated a RAN slicing problem to maximize the total resource allocation success probabilities while providing energy-efficient URLLC services.

The majority of works on network slicing for IIoTs consider single objective-based resource allocation and QoS enhancement [65], [71]. However, for industrial services, the age of information (AoI) [72] is a crucial metric; by objectively capturing the information value from applications' perspective, AoI helps controllers to take up-to-date decisions. Therefore, intelligent slicing solutions for multi-objective resource allocation are desired, where each objective must truly reflect the application-specific connectivity requirements. To this end, we created an example scenario of three industrial monitoring and control classes (slices), each having different time-varying latency and reliability demands on resource allocation. The objective was to maximize the service rate while striking a balance between energy consumption and AoI under slice isolation constraints. To solve the problem, we employed game theory and machine learning (i.e., actor-critic model with a deep deterministic policy gradient (DDPG) [73]) to optimize the network slice configuration policy. For further details, please see [74]. Our simulation results (c.f., Fig. 9) show that the proposed framework can serve, respectively, 50% and 44% more devices on average than the baseline (policy gradient–PG and proximal policy optimization–PPO) approaches. Although DDPG's performance gain comes at the cost of 46% and 50% higher energy consumption than PG and PPO, DDPG's AoI violations are as low as 5% compared to 44% and 42% in PG and PPO, respectively.

C. NR-U: Enabling 5G Coexistence in Unlicensed Bands

Extending the 5G NR operation in the unlicensed bands by NR-U is a major feature in 3GPP Rel-16, which is expected to open new vertical markets and private 5G deployments. Prior to NR-U, 3GPP had proposed a series of LTE extensions (LTE-U) since Rel-13 to extend its operation in unlicensed bands, which led to NR-U standardization. Table I shows the evolution of unlicensed spectrum capabilities in 3GPP releases.

TABLE I
EVOLUTION OF UNLICENSED SPECTRUM FEATURES IN 3GPP RELEASES

Attributes	**3GPP Release**				
	Rel-13	Rel-14	Rel-15	Rel-16	Rel-17
Technology	LAA	eLAA	feLAA	NR-U	NR-U
License-assisted operation	Only DL	Yes	Yes	Yes	Yes
Standalone operation	No	No	No	Yes	Yes
Frequency [GHz]	5	5	5	5, 6	5, 6, 60
Numerology	LTE	LTE	LTE	5G	5G
Aggregated BW [MHz]	80	80	100	800	800

Rel-16 enables NR-U to leverage both the global 5 GHz and 6 GHz bands, while Rel-17 extends NR-U operation to 60 GHz mmWave spectrum. 5G NR-U is the first global cellular standard to support both licensed-assisted access (LAA) and standalone use of unlicensed spectrum. *In standalone operation, no licensed spectrum is necessary, whereas, in LAA, a carrier in the licensed spectrum is required for the connection setup.* The LAA of NR-U unlocks a larger spectrum by which the operators can boost existing cellular deployment, offering higher data rates and a better user experience. Scenarios that can benefit from the LAA are public locations with high user density, such as malls, stadiums, and concert halls. The NR-U ability to operate standalone, without a licensed primary carrier, is significant because it simplifies the private 5G deployment in tenant/owner-controlled nonpublic locations. For the IIoT, this capability is desirable as it opens the road for the deployment of 5G NR-U networks within controlled environments for supporting URLLC services [75]. Additionally, 5G NR-U offers a high degree of mobility because it inherits the coordination between BSs of a cellular system.

The NR adaptation to unlicensed bands requires redesigning the standard procedures, channels and signals to comply with the regulatory requirements. Some of the restrictions imposed by regional regulations include maximum channel occupancy time (MCOT), maximum radiated power, occupied channel bandwidth (OCB), frequency reuse, and dynamic frequency selection. To ensure the high reliability required in many IIoT applications, the coexistence of NR-U with other wireless technologies (e.g., WiFi), operating in the unlicensed spectrum, must also be ensured. WiFi products are already present in the 5 GHz and soon on the 6 GHz unlicensed spectrum with WiFi 6 and WiFi 6E standards [19]. In the 60 GHz unlicensed spectrum, the IEEE 802.11ad and IEEE 802.11ay wireless standards are already used in WiGig products [76].

NR-U, like its predecessor LTE-U, uses a listen-before-talk (LBT) mechanism, which is inherited from LTE LAA proposed in Rel-15 and inspired by WiFi's distributed coordination function (DCF). The alignment of NR-U's channel access mechanism with WiFi aims to achieve their fair coexistence. The problem of fair coexistence with WiFi is extensively studied in the literature, where optimization, game theory, and reinforcement learning (RL) algorithms have been so far applied [77]. However, many challenges remain yet to be solved for reliable and efficient spectrum sharing in unlicensed bands, such as the mechanisms for efficient and secure coordination among technologies or provision of partial and local spectrum information at the controllers [61], e.g., by intelligent interference mapping [63].

D. Energy-Efficient Communication and Computing

Battery-powered or energy-harvesting (EH) devices are expected to form the basis of the IIoT devices' fusion for full-scale sensing and monitoring [78]. Therefore, energy-efficient (EE) communication and the ability to harvest energy from various renewable/RF sources are crucial for autonomous (e.g., reducing labor-intensive battery replacements [79]), prolonged, and environment-friendly operation of IIoT networks, often deployed in harsh locations. For reducing the energy consumption, 5G networks are expected to be ten times more EE than the 4G systems, while *zero-energy* radios are already envisioned for beyond-5G networks [80]. Various power saving techniques in NR Rel-15 and Rel-16 are reviewed in [81], offering flexibility in operation modes. However, wireless power transfer (WPT) and RF EH have made a limited impact in 5G. In beyond-5G, EH techniques will flourish with shorter communication distances, and recent research on intelligent reflecting surfaces (IRS), backscatter communication, and advances in EH methods, e.g., nano-bio sensors [8], handling non-linearities and imperfections in energy storage, waveform design [82].

Nevertheless, in emerging communication-computing ecosystem, future massive IIoT networks will need to adopt system-level—sensing, computing, and communication, architectural, and algorithmic approaches to maximize energy efficiency while maintaining the desired QoS. In RAN, EE methods can be applied at various levels, including network topology/architecture, radio resource and network management, link adaptation, and hardware design and optimization [83]–[85]. Whereas the energy-conservation approaches in the core network mainly focus on the traffic dynamics-aware resource activation, including dynamic traffic engineering, virtualization, and rate adaptation [86]. In 5G-and-beyond networks, new fundamental approaches to EE architectures are required, e.g., configurable modes of operation and activation. Meanwhile, the main EE computing challenges and solutions span across:

- *software/deployment optimization:* includes algorithmic efficiency, optimized allocation of computing resources, virtualization methods.
- *power management:* allows a system to dynamically hibernate its components based on users' activity.
- *cloud computing:* the direct computing-energy cost reduces by moving applications to the cloud.
- *edge/fog computing:* A distributed edge/fog computing model reduces the delay- and security-related concerns of cloud computing and also increases devices' EE by com-

putation offloading [87]. The higher per-bit processing energy cost of edge can be minimized by orchestrating a combined cloud-edge architecture [88].

In applying this ecosystem to IIoT, the challenge is to jointly design and optimize context-aware (i.e., capturing control speed, traffic, channel, computation, and connection dynamics) adaptation of RAN, core network, and computing resources, while considering QoS requirements. Additionally, future EE solutions call for computation-oriented communications [89] and intermittent computing [90] techniques to achieve desired computation accuracy according to the availability of communication/energy resources.

E. Integration of Heterogeneous IIoT Networks

There are many heterogeneous devices and communication protocols in the current industrial environment. As a result, it is becoming challenging to address industrial networks' compatibility and performance issues while integrating them with the existing industrial standards. In recent years, many efforts have been made to achieve integration between existing and emerging IIoT solutions. For example, the authors in [91] proposed integration of LoRaWAN with 4G/5G core network by adding eNB and UE protocol stacks to the LoRaWAN gateway. The proposed solution is transparent to LoRaWAN end devices and the 5G EPC. The authors in [92] studied the coexistence issues between WiFi and 5G in unlicensed mmWave bands. They proposed a spectrum planning mechanism to maximize spectrum efficiency and reduce interference between 5G and WiFi via joint beam selection and resource allocation. The authors in [18] proposed cognitive-LPWAN, which supports the smart management of IoT systems with a variety of low-power technologies (including BLE, WiFi, LoRa, SigFox, LTE-M, and NB-IoT). This study provides an AI-based algorithm to choose different wireless technologies for different IoT applications to meet their respective delay and energy-efficiency requirements.

Meanwhile, terrestrial communication networks alone cannot achieve omnipresent, high-quality, and high-reliability services for their limited radio spectrum, coverage, and operation cost. Visions on future 6G networks have advanced that complimenting and integrating current terrestrial cellular networks with unmanned aerial vehicles (UAVs) and satellites represent a promising solution to support IIoT applications in rural/maritime areas [93]. Integration of cellular, UAVs, and satellites communication for ubiquitous and cost-effective connectivity presents challenges to network control and resource orchestration due to the heterogeneous characteristics and performance of these technologies [94]. Challenges surrounding the coverage metrics of integrated satellite and UAVs networks also arise from the spatial and temporal traffic distribution of service demands of industrial users to which the network control architecture needs to respond dynamically. In this respect, multi-objective resource allocation techniques for integrated satellite-UAV networks (e.g., see [95]) are needed to support dynamic service demands.

F. mmWave-mMIMO Adaptation for IIoT

The capacity boost by mmWave-mMIMO based 5G system is promising for data-intensive IIoT. However, mMIMO systems inherit many challenges that must be addressed before they can be employed in IIoT deployments.

1) Realizing digital precoding schemes for creating beamspace in massive arrays with a large number of antenna elements is challenging since the implementation complexity increases at higher mmWave frequency with wider signal bandwidth [96]. Moreover, in partially-connected mMIMO architectures, the digital precoder has no control over each antenna element's phase currents, which requires exploring fully-connected hybrid mmWave-mMIMO architectures.
2) mmWave channel power-delay profiles are mostly sparse due to narrow beams (array gain) from massive arrays, i.e., multipath components are unavailable due to higher energy scattering. In contrast, MIMO channels benefit from the channel diversity gains in the presence of multipath components [40]. Moreover, the industrial environment is harsh—high degree of scattering due to metallic surfaces [97]. Therefore, it requires exploring the trade-off optimization between array gain (beamforming) and spatial multiplexing gains (channel diversity gains) according to channel state information.
3) Indoor channel conditions are stochastic, causing higher LoS blockage probability and requiring efficient beam management (i.e., tracking, serving) as a part of mmWave initial access mechanisms [98].

G. Securing IIoT in 5G-and-Beyond

In ongoing digitalization drive with *5G-Edge-AI* ecosystem, massive security and privacy challenges arise in delivering resilient wireless services to IIoT. Industrial systems and services are security-sensitive, requiring protection and isolation from cyber threats, especially when sharing resources of a common wireless infrastructure. Consequently, there is a need to boost wireless systems' trustworthiness by integrating various features (e.g., network resilience against failures, secure communication, identity management, privacy, and security assurance) to guard mission-critical systems holistically. Without integrating these strategies into beyond 5G-evolution roadmap, the unsecured IIoT can expose both the service providers and the industrial users. Additionally, 5G's compatibility with existing industrial security standards in vertical domains (e.g., IEC 62443 [99] for automation, transportation, and energy management) must be ensured for 5G's trustworthiness in industrial settings.

Four key dimensions must be considered in 5G-and-beyond architecture to secure IIoT within the *5G-Edge-AI* ecosystem: **Network resilience.** Communication encryption/integrity-protection is critical for vertical applications. However, to secure devices-controller sessions, the service availability and dependability are equivalently important. In this respect, 5G's service-based architecture enhances network resilience by isolation, redundancy, and duplication at network functions and RAN. Moreover, supporting delay-sensitive URLLC traffic in resource-constrained scenarios cannot afford the delays introduced by traditional over-the-top security services. As a result, it is essential to consider other means, e.g., physical layer security and intrusion detection mechanisms for critical infrastructures [99], [100]. In sum, different requirements (delay, power consumption) must be met by the underlying 5G protection solutions depending on how 5G networks and technologies are used by an automation application [12].

Mitigating security threats by automated O&M. The threat landscape continues to grow with the 5G's heterogeneity and complexity, requiring security solutions at multiple levels (e.g., slice, service, resource) across different domains and deployments (e.g., centralized and distributed, physical and virtual deployments). In this scenario, security-related tasks in O&M functions must be trained for automated detection and mitigation. In addition, the enterprises would also prefer to have complete control over management (create, scale, configure) of shared resources and monitoring/troubleshooting the performance and security threats. The real-time QoS monitoring of critical traffic and service availability enable ML/AI-based predictive solutions [101] and avoid imminent failures/threats.

Security and privacy of NPNs. The factory-floor data includes sensitive information, such as subscriber/device, number of active devices, in addition to the user payload data. Consequently, managing data privacy in NPNs overlay with public networks brings many additional challenges. Most importantly, the non-public and public networks' data must be segregated physically or logically and processed separately. Meanwhile, to provide control and manage privacy, the associated functions need to be segregated through physical and logical isolation and third-party APIs [100]. Also, there is a growing need for flexibility in the choice of security mechanisms depending on the network type. For NPNs, universal subscriber identity module (USIM) and certificates for device authentication, identification, and access authorization need to be more efficient. Further, dedicated NPN certificates administered locally can be leveraged to enable greater security customization. The corresponding data confidentiality and integrity algorithms need to be equally flexible for smooth network integration.

Edge AI for secure 5G. The proliferation of IIoT devices on the factory floor has brought its own set of problems. In particular, numerous IIoT network points are susceptible to failure owing to the lack of inherent security measures that have caused security gaps for industrial plants. As a result, attackers may exploit several weak entry points (e.g., sensory devices) in the IIoT ecosystem. Therefore, AI-driven edge computing plays a significant role in its computation, communication, caching, and control capabilities to mitigate the IIoT security challenges. In practice, edge-AI deployment on the factory floor minimizes the number of points of failure (or access points) that intruders can exploit [102]. Further, edge-AI in IIoT allows factory sites to install the most appropriate and intelligent security solutions in their vicinity to decrease the threat of localized industrial data leakage during transmission instead of transmitting to the cloud platform that minimizes security and privacy risks [103]. Consequently, the critical research challenges on the edge AI-driven security issues include holistic intrusion detection and analysis models for supporting IIoT applications (e.g., industrial V2X) [104], [105]; different cryptography techniques while preserving data security and privacy [106]; secure data aggregation; secure data deduplication; secure computational offloading, and edge-enhanced data analysis [107].

The envisioned AI-on-5G has kickstarted a whole new evolution of graphics/central/data processing units, integrated by yearly leaps of chip design architectures such as NVIDIA Ampere, Grace, and BlueField, which brings new possibilities in the IoT-5G scenario [108]. With accelerated computing power to support the cloud, 5G industrial edge, and devices, security solutions will enter a new era of automated security services in real and virtual connected systems [108], [109]. For example, federated and reinforcement learning-based collaborative attack detection and defense have been discussed for wireless network jamming attacks, which are emerging cyber threats in addition to other intrusions [105], [110]. Moreover, blockchain technology is also expected to play a vital role in 5G-enabled IIoT to handle trust management and privacy issues via the implementation of distributed ledger and smart contracts [111].

VI. CONCLUSIONS

5G is rapidly evolving beyond current 3GPP releases with enhanced technologies offering new features to serve challenging IIoT services even beyond Industry 4.0. In this paper, we elaborated the expanding wireless ecosystem with industrial-centric features, as an enabler for fine-grained and wide-scale connectivity, in the current 5G architecture. We also discussed the transformative technologies and their potentials for meeting enhanced (mmWave-mMIMO) channel capacity, positioning, and (non) real-time offloading, data analytics with IIoT-edge-cloud ecosystem. Later, we delved into emerging design trends and associated research challenges while considering state-of-the-art works stemming from industry and academia. In this respect, we presented the IIoT network deployment options, including i) giving control and freedom to industrial operators to customize their RAN, ii) private networks with various spectrum usage options, iii) 5G NR-U for unlicensed bands, iv) RAN slicing options. We also discussed the significance of energy-efficiency and energy-harvesting for IIoT, which will form the basis of the IIoT devices' fusion for full-scale monitoring/sensing. In the end, we discussed key dimensions of security and privacy issues for IIoTs in a growing threat landscape with increasing complexity and heterogeneity of future wireless networks.

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