Factory 5G

A Review of Industrial-Centric Features and Deployment Options

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Abstract—Fine-grained and wide-scale connectivity is a pre-condition to fully digitalize the manufacturing industry. Driven by this need, new technologies such as time-sensitive networking (TSN), fifth-generation (5G) wireless networks, and industrial Internet-of-things (IIoT) are being applied to industrial communication networks to reach the desired connectivity spectrum. With TSN emerging as a wired networking solution, converging information technology (IT) and operational technology (OT) data streams, 5G is upscaling its access and core networks to function as an independent or a transparent TSN carrier in demanding OT use-cases. In this article, we discuss the drivers for future industrial wireless systems and review the role of 5G and its industrial-centric evolution towards meeting the strict performance standards of factories. We also elaborate on the 5G deployment options, including frequency spectrum allocation and private networks, to help the factory owners discern various dimensions of solution space and concerns to integrate 5G in industrial networks.

Index Terms—5G, industry 4.0, industrial IoT, private networks, radio spectrum, security, TSN, time-sensitive communication.

I. INTRODUCTION

The envisioned Industry 4.0 defines the transformative progression of industrial manufacturing systems towards future smart factories, offering flexibility and efficiency [1], [2]. The smart factories of the future are characterized by [3], [4]: i) holistic management in the entire value chain through horizontal and vertical integration of operation technology (OT) and enterprise-IT domains, ii) modular and customizable production lines, iii) support for mobility use-cases including mobile robots, control panels, and automated guided vehicles (AGVs). However, such progression requires seamless connectivity of people, machines, and computing resources in industrial manufacturing processes.

Connectivity is fundamental to collect and utilize data for bridging the divide between physical and digital worlds, and developing new revenue streams and cost savings. But, the challenge is to satisfy the diverse connectivity demands on reliability, low-latency, and capacity. The industrial OT networks include diverse solutions, such as Ethernet-based networks (e.g., PROFINET, EtherCAT) and field-buses (e.g., PROFIBUS) [5]. Meanwhile, the IEEE 802.1 time-sensitive networking (TSN) task group is developing a set of standards

to extend the best-effort Ethernet networking model to provide deterministic streaming services. Concurrently, the TSN profile (defining features, options, requirements) for industrial automation is being defined by IEC/IEEE 60802. These initiatives will provide enhanced industrial Ethernet solutions for enterprise-wide connectivity, support the capabilities of industrial Ethernet variants, and increase hardware homogeneity on the factory floor [6], [7]. However, the full-scale connectivity of the entire value chain requires a combination of wired and wireless solutions to support massive sensing, mobility, and customizable production lines. Nevertheless, wireless systems are still not too popular for reliability and performance concerns of industrial-grade deterministic communication [8]. Thus, the current wireless networks exist on a precarious scale, only penetrating to process automation or other non-critical applications [9].

Over the years, cellular systems have been optimized to provide extended coverage and data rates for mobile Internet. However, connectivity demands of the vertical industries, such as factory and building automation, energy, and transportation, are substantially different. To this end, 5G networks are upscaling in terms of capability and flexibility, while the network design stretches beyond consumer-oriented mobile broadband services by introducing features tailored for IoT, industrial IoT (IIoT), and connected cyber-physical systems (CPS) [10], [11]. IIoT describes a communication network of industrial objects (machines, devices, and processes) for reliably exchanging monitoring/control data while CPS uses IIoT to provide a consistent (synchronized and interactive) digital description of the objects [12]. In fact, 5G introduces three main connectivity services: enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communications (URLLC). The apparent industrial use-cases of these services are shown in Fig. 1, yet by combining these services, 5G can support extreme variations of IIoT applications.

Although 5G becomes a unified connectivity fabric, the seamless introduction to the factory floor raises several questions and challenges about the connectivity gaps 5G can fill, how to integrate it with the TSN, and whether it satisfies the time-sensitive communications (TSC) targets while keeping business-critical data local. Therefore, different businesses and mobile network operators (MNOs) are concurrently seeking to understand the 5G architecture's design and optimization (the extending ripple in Fig. 1) to expand their business models beyond mobile broadband [14], [15]. In this direction, private (non-public) 5G networking models [16] and associated spectrum licensing options need to be explored carefully in realizing dedicated, customizable, and cost-effective services

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Fig. 1. 5G's design and optimization for diverse industrial applications. 3GPP Release 15 (Rel-15) defined eMBB, mMTC, and URLLC services for 5G New Radio (NR); Rel-16 focused on IIoT-related enhancements, including URLLC for TSC, 5G-TSN integration, localization services, private networks (PN), network slicing, and NR on unlicensed bands (NR-U) for URLLC; Rel-17-and-beyond will cover further improvements in PNs, convergence with industrial networks, network automation, and NR-Light for new IIoT use-cases [13].

for industrial use-cases [17].

While reflecting upon such concerns and challenges, this article presents a technical review of 5G's industrial-centric features and deployment options in the ongoing efforts to develop *Factory 5G* networks, i.e., private 5G networks for industrial use. The term *factory 5G* is specifically used in this article to refer to a private 5G network deployed for the process/manufacturing industry. We begin with the key drivers for enhanced industrial wireless and 5G use-cases in Sec. II. Sec. III discusses industrial-centric 5G RAN (i.e., New Radio (NR)-based radio access network) and Core features, while Sec. IV and Sec. V explore spectrum usage and private network deployment options, respectively. Concluding remarks are given in Sec. VI.

II. DRIVERS FOR ENHANCED INDUSTRIAL WIRELESS

By full mobility support and the replacement of cables, wireless automation has the potential to transform industrial production systems. However, until recently, the wireless communication sector lacked a clear understanding of integration scenarios and dependable communication requirements of industrial use-cases. The 3GPP studies (e.g., [18], [19]) and close collaboration between wireless communication and industrial sectors have led to the industry-specific design of time-sensitive, ultra-reliable, and massive connectivity features in 5G networks. These features can serve wide-range of use-cases on the factory floor, independently or jointly (by augmenting wired industrial solutions) as shown in Fig. 2. Particular needs for enhanced wireless systems arise from

- **Dynamic network customization:** Scaling capacity, speed, and control according to changing manufacturing demands requires rapidly reconfigurable and modular production lines, termed as swarm or matrix production [4], [20]. However, due to costly and complex cable management, the layout of production lines is mostly statically configured. By leveraging wireless connectivity, the desired flexibility can be achieved; however, radio resource allocation and network management become challenging.
- **Mobility and collaboration:** Support for mobile objects (AGVs, robots, and control panels) and their collaboration

in flexible/modular manufacturing is vital to automate recurring, labor-intensive, and costly tasks. Support of mobility and collaboration requires robust wireless connectivity to guarantee fail-safe operation [5].

- **Data-intensive use-cases:** To enable remote inspection, monitoring, and surveillance, human-machine interface (HMI) applications for real-time situation awareness are needed, including control panels, massive diagnosis data upload, AR/VR, and HD video/audio [18]. These use-cases are data-intensive and radio resource demanding.

Table I gives application area-wise industrial use-cases and key performance indicators (KPIs) based on 3GPP studies [18], [19]. Meanwhile, the most relevant 5G use-cases across various industries and their influence with respect to generated traffic volume on overall network architecture is projected in [21]. These studies underscore the need for a versatile wireless solution to satisfy diverse connectivity requirements, ranging from time-sensitive to data-intensive communications with support for mobility and scalability. The wireless standards explicitly designed for industrial communication (e.g., ISA100.11a and WirelessHART) are limited in scope; using the low-rate IEEE 802.15.4 standard, they offer limited rates, coverage, and scalability. Conversely, 5G's flexible design and its targeted evolution can provide unified industrial connectivity using a service-oriented approach. On the downside, compared to the ad-hoc and unlicensed spectrum-based operation of IEEE 802.15.4, a factory 5G deployment requires both technical and business evaluations to demonstrate its techno-economic feasibility. The technical challenges that persist today are, i) the feasibility of satisfying industrial KPIs and the convergence with industrial networks, and ii) the control over business-critical data and the network/service customization. Whereas the business viability of factory 5G is too early to predict, both the vendors and operators are struggling to define a clear roadmap of factory 5G rollout (i.e., based on early-stage testbeds [4]). Besides, the figures on the business value that the factory 5G will create are much-hyped than proven to determine a concrete return on investment (ROI).

Nevertheless, to mitigate technological concerns, 5G is unfolding NR-RAN and core network (CN) design consistent

Fig. 2. Factory 5G use-cases in a converged industrial network.

TABLE I
FACTORY OF FUTURE APPLICATIONS AND USE-CASES, WITH PERFORMANCE REQUIREMENTS (BASED ON [18], [19]).

Application areas	Use-cases	KPI				
		Reliability	Latency	Data rate	Payload	Devices
Factory automation	Motion control		0.5–2ms	1–5Mbps	20–50B	20–100
	Control-to-control	99.9999%	10–50ms	–	1kB	5–10
	Mobile robotics (cooperative)		1–50ms	–	40–250B	100
Process automation	Closed-loop process control	99.9999%	≤ 10ms	–	20B	–
	Process monit.	99.99%	50–100ms	0.5–2Mbps	–	100–1000
	Condition monit. (safety)	99.9%	5–10ms	0.1–0.5Mbps	–	>1000
	Condition monit. (interval/event-based)	99.9%	50ms–1s	0.1–0.5Mbps	–	>1000
HMI & production IT	Mobile control panels with safety control	99.9999%	4–12ms	–	40–250B	2–4
	AR/VR	99.9%	< 10ms	5–25Mbps	–	10–20
Logistics & warehouse	Mobile robotics (video op.)	99.9999%	10–100ms	–	15k–250kB	100
	Mobile robotics (std. op.)		40–500ms	–	40–250B	100
Monit. & maint.	Massive WSNs		Non-critical, massive devices, energy-aware			

with industrial-grade QoS targets; end-to-end (E2E) latency of $< 1\text{ms}$ and reliability in the order of $1 - 10^{-6}$ [19]. These stringent E2E performance targets require joint dimensioning of RAN and CN, while two broad directions are:

- Industrial-centric enhancements in radio and core network features for time-sensitive wireless communications and integration with wired Ethernet (e.g., TSN).
- Offering various network/service deployment options with *private 5G* to meet industrial requirements on, i) dedicated coverage and guaranteed QoS, ii) keeping business-critical data local, secure and private, and iii) flexible spectrum usage options.

III. 5G SYSTEM FEATURES AND ENHANCEMENTS

A 5G system (5GS) consists of user equipment (UE), RAN, and CN. The CN comprises control plane (CP) for signaling, user plane (i.e., user plane function-UPF) for data connectivity, and provisioning/management layer. The division between control and user planes provides flexible network deployment/operation, where only Ethernet/IP connection is visible to a 5GS user (e.g., an industrial network).

A. 5G-RAN Design for Time-Sensitive Communications

To support critical data flows, 5G NR introduces several URLLC features broadly grouped into [13]: low-latency, ultra-reliability, scheduling, and over-the-air time synchronization. For low-latency communications, NR provides adjustable resource granularity and mini-slots in a radio frame. The former enables shorter time slots while the latter allows prioritized transmissions at other than slot boundaries. Moreover, NR avoids handshake-based transmission grants by semi-persistent and configured grant scheduling schemes to enable periodic transmissions on the pre-configured resources. Also, to provide prioritized access to URLLC traffic, NR introduces uplink/downlink preemption by which a URLLC transmission can preempt an ongoing non-critical transmission. Besides, NR supports retransmissions within lower latency bounds by fast packet processing.

NR meets URLLC reliability targets using ultra-robust modulation and coding (MCS) schemes for the data and control channels. To avoid the extra degree of uncertainty in control channels, NR supports grant-free transmissions. Besides, various diversity schemes such as multi-antenna techniques, dual-

Fig. 3. TSN-over-5G by mapping of 5G and TSN features.

connectivity, multiple carriers, and packet duplication are part of the URLLC reliability toolbox [5].

Time synchronization is an essential element of 5GS deeply embedded into its radio/core network entities through a telecom profile of the precision time protocol (PTP). In Rel-16, the time synchronization support is extended to UE-level for time-sensitive applications, using reference time indication from the BS and timing-advance (TA)-based adjustment of the propagation delay (PD) at the devices. However, it is hard to meet the tight synchronization budget of $\leq 1\mu\text{s}$ in the 5GS due to BS time alignment errors, limited TA granularity, and other timing and multipath propagation errors [22]. Therefore, further study and analysis is needed on enhanced PD compensation techniques with high-resolution TA or round-trip-time-based PD estimation with dedicated signaling, or other innovative directions [23]. As the synchronization complexity is accentuated in converged wired-wireless networks, the readers may refer to [24], [25] for synchronization techniques/analysis in such scenarios.

Note that all these RAN features cover the non-trivial design aspects for time-sensitive communications. Further, the design and assessment of these features in dynamic (w.r.t. multipath fading, blockage, interference) industrial wireless channels require statistical learning and analysis frameworks [26]. This is because the statistical channel models, often developed based on measurements [5], cannot capture the environment-

specific conditions, correlation of events, and occurrences of performance disrupting rare events.

B. 5G-Core Network Design for TSN Integration

The 5G core network provides various mechanisms for greenfield industrial deployments and to support interworking with Ethernet-TSN networks, such as:

- 1) Packet duplication by establishing redundant user plane paths within RAN, core, and transport network [27]. This feature is similar to TSN's frame replication and elimination for reliability (FRER) features defined in the IEEE 802.1CB-2017 standard or parallel redundancy protocol (PRP) protocol specified in IEC 62439 standard for industrial Ethernet. FRER protects against packet failures and latency violations by transmitting every data packet concurrently over two independent paths.
- 2) Native support for Ethernet services and procedures, enabling integration with the industrial Ethernet networks.
- 3) Network slicing, which can span all 5GS or even multiple operators, allows creating virtual networks over a common physical network, each capable of providing negotiated QoS to a private customer. Network slicing techniques can be exploited to isolate TSN-related control/data traffic in 5G-TSN integration scenarios and to realize factory 5G over a public network (see Sec. V).

- 4) Edge computing environment to bring network functions close to wireless edge to improve privacy and service performance for real-time control. Edge computing can also be applied to the Rel-17 feature of time-sensitive device-to-device communication in TSN via UPF [28].

These features manifest the 5G's integration path with TSN to establish combined wired-wireless solutions for full-scale industrial connectivity. The 5G-TSN integration can enable new use-cases or migrate the existing ones requiring deterministic communications between end-devices and the remote controllers. Similar to 5G URLLC toolbox, TSN provides an open set of standards for guaranteed latency, ultra-reliability, time synchronization, and resource management, with Fig. 3 illustrating the mapping of 5G URLLC toolbox and TSN toolbox of standards.

3GPP Rel-16 introduced TSN translator (TT) functions to interface a 5GS to an external TSN network as a (set of) virtual TSN-capable bridge(s) [22]. TTs expose the necessary 5GS control plane and user plane interfaces for handling TSN's bridge configuration, flow control, and time synchronization while masking 5GS internal functions. In particular, with TT functionality at the control plane, 5G TSN application function (AF) provides the management function to interact with the TSN controller (CNC-central network controller) according to IEEE 802.1Qcc, to report capabilities and receive configuration from CNC via a network management protocol [28], [29]. Here, 5G AF is an example of network function virtualization (NFV) for allocating/configuring 5G network resources for TSN streams. Meanwhile, 5GS provides a virtual bridge per UPF on the network side using NW-TT as a gateway to the TSN, with device-side (DS-TT) acting as a port for a 5G wireless device. For synchronization, 5GS uses an internal clock for adjusting the residence time of TSN's synchronization messages in the 5G system (i.e., between NW-TT and DS-TT) according to IEEE 802.1AS. Further details on 5G-TSN integration and research challenges are available in [17], [28], [29].

IV. RADIO SPECTRUM OPTIONS FOR FACTORY 5G

Spectrum policy—*how the spectrum is licensed*—is critical to 5G solutions and services. Though spectrum allocation is essential for growing data rate demands; it is critical for industrial applications with stringent QoS requirements. A key question for industries is which spectrum is suitable for factory 5G. Currently, spectrum licensing authorities are at different stages of 5G spectrum assignment. The new radio spectrum for 5G is being allocated on low-, mid-, and high-band frequency ranges, providing different performance and coverage characteristics (see Fig. 4). Of these, the mid-band 3.3–4.2GHz spectrum is deemed ideal for 5G signaling, giving optimal tradeoff between bandwidth, distance coverage, and building penetration. The harmonized use of this spectrum range for 5G services is under consideration worldwide, while in the EU, the 3.4–3.8GHz band has already been harmonized. Meanwhile, in the U.S., the 3.55–3.70GHz band, called citizens broadband radio service (CBRS), allows 5G network deployments through shared access using a three-tiered sharing

Fig. 4. 5G spectrum allocation in different bands, with key characteristics and band-specific use-cases.

mechanism, including incumbent, priority access licenses, and general access licenses.

A. Dedicated Spectrum for Industries

Traditionally, spectrum policy follows a *market-based* approach—using auctions to ensure efficient spectrum allocation for new use-cases. However, spectrum reservation for localized use is an unprecedented approach, promoting *industrial* policy. The idea of dedicated spectrum allocation for industries was initially promoted by Germany, citing that: 1) many factories are located in rural areas where MNOs will never utilize the spectrum, 2) only dedicated spectrum will enable a leading role in 5G applications, 3) it will allow industries to operate a private 5G independently and protect trade secrets.

At present, Germany has reserved 100MHz in the 3.7–3.8GHz band for local licenses, while the UK has made the 3.8–4.2GHz band available through shared/coordinated spectrum access for local licenses. Meanwhile, Netherland and Sweden have proposals to allocate at least 80MHz in local licenses in the mid-band. A comprehensive snapshot of spectrum allocations for industries is available at [30].

B. Alternative Spectrum Access Approaches

Although *clean and dedicated* licensed spectrum is preferred for industrial 5G, there could be several spectrum usage alternatives for industries without spectrum reservation, e.g., through spectrum sub-leasing from MNOs, (licensed) shared access, and unlicensed spectrum. Another alternative is to use licensed spectrum under agreement with the mobile operator. There is precedence for this, with some private LTE networks using this model typically for large, high-value clients. Usually, facilities with demanding QoS prefer a licensed spectrum to avoid any risk of communication failures. This still holds in the 5G era; however, emerging technologies (e.g., spatial diversity, artificial intelligence (AI)-enabled spectrum sharing and interference mapping) are empowering to build robust wireless networks even over license-free and shared bands [31], [32]. Also, NR-U, which enables NR deployment in unlicensed bands, is expected to be enhanced for industrial use-cases in Rel-17 [13]. Nevertheless, while considering industrial use-cases' requirements, a portfolio of spectrum usage options can be developed, as shown in Fig. 5.

V. FACTORY 5G DEPLOYMENT OPTIONS

Private networking is another industrial-centric 5G feature to support factory automation with desired flexibility. 5G private networks give complete control over the various critical network aspects, including capacity and coverage, isolated use of network resources, and on-demand customization. 3GPP defines such networks by the term non-public networks (NPN). Private 5G offers flexible deployment options using physical or virtual elements of a public cellular network, where the private and public data can be segregated to maintain security/privacy [16].

A. NPNs Functional Perspective

From a functional standpoint, 3GPP defines two types of NPNs: standalone (aka isolated NPN [16]) and public network-integrated (PNI), while the applicable model depends on the use-case and its requirements (see Fig. 6).

1) *Standalone NPN*: A standalone¹ NPN has all the functions (control and data planes) located inside the factory, while it can use any of the earlier-discussed spectrum options. Although a dedicated 5G may incur high cost and management complexity, it gives scalability and security gains.

2) *PNI-NPN*: Depending on how the 5G functional elements are distributed over the deployment area, this option provides different integration levels with the public network. Consequently, a non-service provider (e.g., an OT company) will need to cooperate with an MNO for network functions sharing, network management, service continuity, and spectrum access. The main options are:

- **NPN hosted by public network:** In this model, the public network dedicates user and control plane resources to an enterprise using network slicing or APN (access point name) functionality. A network slice comprises a dedicated or shared subset of network resources (e.g., processing power, storage, and bandwidth). It can support heterogeneous service classes concurrently, e.g., an eMBB slice supporting data-intensive while the other time-sensitive applications. Also, edge computing, as a part of a network slice, can enable network functions as software instances for industrial use-cases [33]–[35]. Using this model, enterprises can get a private network benefits without upfront-installation and operation cost/complexity.
- **Shared RAN:** The enterprise only shares RAN with the public network, enabled by 3GPP RAN sharing specifications [36]. As 5G's user plane and control planes remain local, the data/signaling remains local at the factory premises.
- **Shared RAN and control plane:** This option shares RAN and control plane with a public network. The local user plane can provide access to the application layer data at MEC, e.g., for real-time control communications, and also enable other value-added services such as data analytics, location-based services, and data caching. Note that control plane placement becomes critical when extensive control and signaling are involved.

¹Henceforth, the term “standalone” must not be confused with the 3GPP defined terms “non-standalone or standalone 5G” for the 5G deployment options with or without the support of a 4G network.

Fig. 5. Spectrum usage options for vertical industries based on spectrum regularity models.

Fig. 6. Deployment options for 5G non-public networks (NPN). From model (a)–(d), the solution cost and performance guarantees reduce, while data privacy, security, and dependency concern increase (based on [37, Table 5]).

B. NPNs Operational Perspective

Concerning the operation models, NPNs can be placed along three dimensions: management, ownership, and spectrum policy. Examples can be:

- **MNO-provided service:** MNO owns/manages the private 5G using a licensed spectrum.
- **Self-managed service:** an OT company exclusively owns/manages the dedicated NPN using leased, local, or unlicensed spectrum.
- **Hybrid solution:** OT manages its private 5G and partners with MNO for licensed spectrum, or MNO provides 5G solution using OT's private spectrum.

The management/monitoring tasks in private 5G define how an OT company can manage (create, scale, configure) and monitor a deployment model's network functions. Usually, OTs prefer to have complete control to manage and adapt network functions and resources and troubleshoot the NPN's behavior according to industrial processes' functional and performance needs. Meanwhile, real-time monitoring of critical traffic's QoS and service availability is a prerequisite to employ ML/AI-based predictive management solutions [38]. In this respect, the ongoing 5G softwarization efforts (e.g., OpenAirInterface, OpenRAN, SDN/NFV [17], [33], [34]) will accelerate factory 5G's cost-effective deployments and customization.

C. Security and Privacy in Factory 5G

Apart from encryption and data integrity, the privacy and security concerns/solutions of private 5G deployment span across service resilience against failures and radio jamming, service isolation, and interoperability with existing industrial security functions. In any deployment model, 5G's service-based architecture provides resilience by redundancy/duplication of network functions and resources, while radio jamming attacks can be avoided by combining techniques, such as spectrum monitoring, dynamic spectrum access, beamforming [31], [39].

Traditionally, OT networks are physically isolated by perimeter protection and access control mechanisms [40]. In this respect, standalone NPN can provide the highest security via physically isolated network elements; however, PNI-NPNs need logical isolation/access authorization and additional E2E encryption and integrity protection mechanisms. For standalone NPNs, 5G supports operator-controlled alternative device authentication methods (e.g., key-generating EAP-TLS) [41]. In contrast, for PNI-NPNs, using 5G-AKA and EAP-AKA authentication methods is mandatory, together with USIMs for public network authentication. When the NPN is deployed as a slice, slice-specific authentication can be optionally performed after primary device-network authentication [41].

To avoid the overhead and extra delay of additional integrity protection measures and E2E encryption, other solutions, e.g., physical layer security and intrusion detection mechanisms, must be investigated. Besides intrusions, network jamming attacks are potential cyber threats for which federated and reinforcement learning-based collaborative attack detection/defense mechanisms are emerging [42].

VI. REFLECTIONS AND CONCLUSIONS

Connectivity is the panacea of the future smart manufacturing's strive for digitization and agile factory operations. With 5G wireless, this vision is becoming more plausible via mobility support, augmenting workers, collaborative robotics, edge computing and control, and machine vision. The industrial applications entailing these functions have diverse and stringent KPIs for which emerging 5G networking capabilities and services are creating an opportunity to realize wireless industrial control. However, as a factory 5G solution, it has to satisfy the KPIs and deal with the integration, management, and operation complexities of OT networks. In this article, we discussed the driving industrial use-cases for ongoing 5G design and optimization and reviewed the industrial-centric network features, deployment models, and spectrum options.

3GPP Rel-16 and Rel-17+ are continuously studying and specifying enhancements to handle industrial use-cases. Even so, it is early to say when such industrial-friendly deployments will be in place due to the gap between product development and industrial acceptance and needs. Consequently, the technical feasibility and solutions for industrial KPIs is one side of the coin. The other side is multi-faceted, i.e.:

- 1) The 5G URLLC features address non-trivial issues, but their fail-safe design and validation for dynamic industrial

wireless channels require new statistical frameworks and data-driven strategies,

- 2) To create demonstrable trust, validation and evaluation in real deployments is needed, and
- 3) Cross-industry communication, standardization, and regulations must be more inclusive.

For instance, related to point (2), recent first measurement results reported in [43] on a Rel-15-based private 5G network have shown a need to reduce the upper percentile of packet latencies and improve the consistency of the packet delays in overall 5G systems. The readers are encouraged to refer to [43] and the references therein for further insights. Therefore, in demonstrating factory 5G's potentials, emphasizing future research and development imperatives, and removing the silos between telecom and automation industries, all these aspects are crucial to address. Also, the real value of factory 5G will be defined by its role in improving the manufacturing processes in terms of their responsiveness to the demand, efficiency, capacity utilization, and product/service customization and innovation.

Critical is to discover/develop anchor use-cases showing 5G's effectiveness in performance, safety, and ROI. The promising anchor use-cases for which factory 5G efforts are noticeable include network robots/AGVs, vision and augmented reality, intelligent edge for closed-loop control, and massive WSNs. For instance, for the emerging matrix or additive manufacturing concepts, requiring reliability, timeliness and synchronization for connected mobile robots/AGVs coursing on condition-based dynamic routes instead of prevailing predefined routes, the 5G RAN and Core enhancements are fitting for low-latency access to edge computing resources. Still, the remaining challenges are network optimization (coverage and scheduling) under operational dynamics. Additionally, 5G broadband can support vision- and augmentation-related uses-cases for virtualization and remote maintenance, respectively, for a limited set of devices. However, in massive connectivity for critical production processes or interactive-XR for collaborating field agents or haptic control, maintaining minimum peak data rates with low-latency remains open for further enhancements. Meanwhile, the integrated communication, sensing, and localization is still an open issue for the context-aware human-machine interactivity.

For integration with the Ethernet/TSN networks, 5G already provides end-to-end support for scheduled flows, synchronization, and reliability. Still, further work is needed to translate TSN resource allocations and time synchronization within the converged 5G-TSN system in challenging industrial RF environments.

Spectrum usage options and different network deployment models will be decisive in factory 5G's success. The composite deployment models must consider all the stakeholders, including spectrum authorities, MNOs, and OT/IT technology providers. For alternative spectrum policies/usage options, a cost-benefit analysis is needed while considering:

- Dedicated spectrum is expensive and ROI will depend on anchor use-cases,
- MNO-owned spectrum portfolio can provide network scalability and harmonized indoor/outdoor coverage, and

- NR-Unlicensed with URLLC enhancements might be more sustainable for small/medium enterprises in joining digitalization drive.

The standalone 5G deployment model can enable dedicated support for critical use-cases while providing necessary privacy and security features. Whereas, for public network integrated private 5G, the solution providers need to reduce the operation and management complexity, and provide autonomous solutions to network operation, optimization, on-site and remote functional splits, new service deployment and QoS assurances for multiple scenarios and services.

Above all, private 5G wireless brings along many security concerns to the factory floor, especially when sharing resources with a public network. 3GPP offers solutions to increase resilience of private networks by duplication of network functions/resources, and service/slice authorization and isolation. Against radio jamming attacks, the solutions can be devised by combining 5G's dynamic spectrum monitoring and allocations and beamforming techniques. Meanwhile, to reduce the additional communication overhead of security measures, new techniques such as physical layer security and federated learning are promising but require realistic suitability analysis for real-time control and analytics.

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