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Software-based 5G Industrial Wireless
Private Networks

*Challenges and Opportunities for Mission-Critical and
Time-Sensitive Applications*

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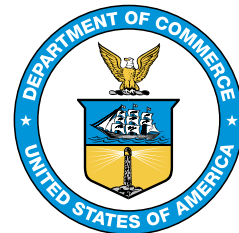
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Abstract

There is a growing interest in the industrial wireless community to utilize wireless communications for industrial applications. Among different wireless technologies, 5G technology offers remarkable architectural flexibility and is designed to accommodate various types of applications, making it an excellent solution for Industry 4.0 applications and beyond. Especially when latency and reliability are major concerns for industrial wireless, the 5G Ultra-Reliable Low Latency Communications (URLLC) service ensures the ability to support industrial control and mission-critical applications. Among different next-generational private network implementations, software-based private 5G networks have emerged as a promising candidate for industrial use cases, providing advantages such as open-source code, reduced dependency on proprietary infrastructure, and lower deployment costs. However, the limitations of computing hardware, complex management and configuration processes, alignment with industrial communication requirements, and the difficulty of evaluating performance in harsh industrial environments all present significant challenges in the adoption of software-based 5G deployments.

In this report, our objective is to perform a technology analysis of software-based 5G networks for industrial applications, focusing primarily on the aspects of technology adoption difficulties, performance compliance, industry expectations, network measurements, and performance evaluation. In addition, we present results from a series of interviews with stakeholders in the industrial community to better understand their needs. We highlight key gaps and expectations for 5G adoption according to their feedback. Our objective with this report is to provide a unified document that supports 5G and beyond technologies for mission-critical and time-sensitive applications. We identify and discuss critical challenges, missing elements, and future opportunities based on our experimental experience with 5G-integrated testbeds, real-world performance evaluation, and feedback from the industrial community.

Keywords: 5G, 6G, software-based networking, vRAN, industrial wireless

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1 Introduction

The use of wireless communications in industrial applications is gaining significant interest because of the potential to reduce costs and improve efficiency. Wireless network transformations reduce installation and maintenance costs, offer greater flexibility and scalability, and enable communications in environments where wired connections are impractical. Industrial wireless networks (IWNs) face many challenges due to the uncertainty of wireless propagation channels, radio frequency (RF) interference sources, and meeting the stringent network requirements of industrial use cases. With the advent of Industry 4.0, and the transition towards Industry 5.0, there is increasing demand for higher data throughput, reliability, lower latency, and support for a diverse range of applications [1]. These demands hinder the deployment of existing systems and drive the development of improved industrial wireless systems to satisfy these requirements.

5G, which is defined as a series of standards by the 3GPP starting with Release 15 [2], has emerged as a strong contender for industrial wireless communications. Although its predecessor, LTE, was primarily designed for broadband applications, 5G is designed to accommodate multiple service categories including: Enhanced Mobile Broadband (eMBB), massive Machine-Type Communications (mMTC), and Ultra-Reliable Low-Latency Communications (URLLC) all in a single wireless communications solution. The flexibility in its architecture, configuration setup, and network slicing capability allows 5G to support various applications across different vertical sectors. Example use cases for different service categories, as proposed by the International Telecommunication Union (ITU) [3], are illustrated in Figure 1. Beyond these capabilities, 5G introduces several other key advancements, including the use of mmWave technology, network disaggregation through virtualization and softwarization, and the incorporation of emerging technologies including Software-Defined Networking, Device-to-Device communication, Mobile Edge Computing, and more. These features make 5G a highly adaptable and scalable solution for industrial applications. Appledore et al. predicted that private 5G network deployments will amount to 232 billion dollars annually by 2027 in [4].

However, several concerns and challenges hinder the adoption of 5G wireless technology for many industrial use cases. 5G standardization and implementations are continuously under development, particularly in areas such as URLLC and wireless Time-Sensitive Networking (TSN), which are important for meeting communications requirements of mission-critical applications. The harsh industrial radio environments further complicate the ability to maintain highly reliable and low-latency communications. Furthermore, according to the feedback we collected from the industrial wireless community, the slow transition cycle and high upgrade costs may not justify the benefits that 5G provides, and these concerns are described in Section 2. The complexity of 5G network management compared to other existing wireless systems, along with the compatibility of devices and infrastructure support, presents further challenges. Finally, there are gaps between 5G implementations and market expectations, hindering widespread adoption. This report identifies the gaps in 5G, using NIST's expertise and feedback from key industrial stakeholders, to signal 5G

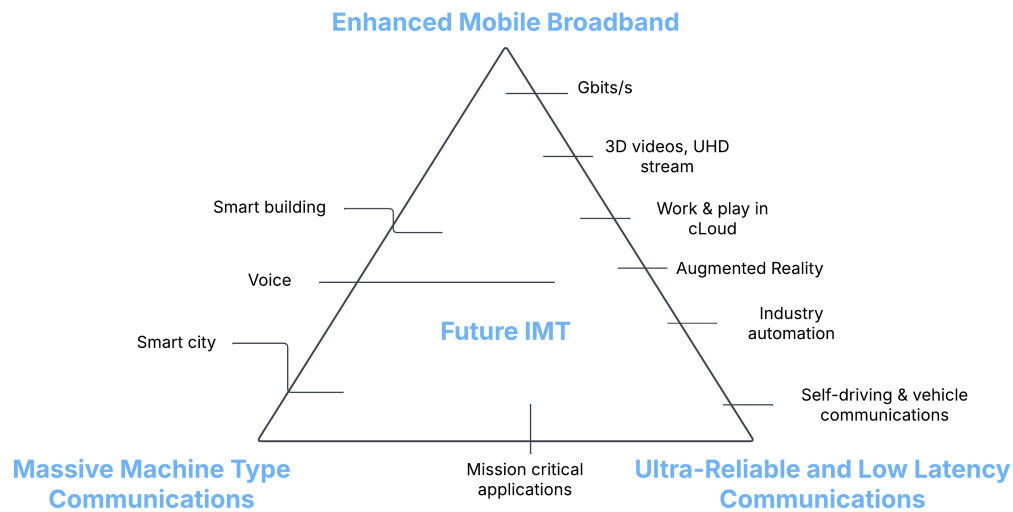


Figure 1: Use scenarios for three service categories of International Mobile Telecommunications (IMT), which is recreated here from [3]

standards developers and researchers on what should and must be addressed going forward.

1.1 Software-based Private 5G Networks

Among various 5G implementation options, software-based private 5G networks have emerged as an intriguing solution. Public 5G networks, which are managed by mobile network operators and accessible to the general public, pose the potential risk of data exposure. Transmissions could be affected by network congestion from general public traffic. In contrast, private 5G networks offer a higher level of security and greater network control compared to public networks, making private deployments more suitable for mission-critical use cases.

Leveraging the network function virtualization of the 5G core and gNodeB (gNB), the entire 5G network can be programmed and deployed on commercial off-the-shelf hardware or general-purpose PCs, eliminating the need for expensive proprietary equipment. Softwarization of 5G networks allow for a more flexibility and dynamic network deployments, where different network functions can be instantiated, moved, upgraded, or scaled on demand. Furthermore, well-developed open-source solutions further minimize reliance on specific vendors, making software-based private 5G networks especially popular among system integrators. Several open-source options are available for the 5G core, including Open5GS [5], Free5GC [6], Open5GCore [7], and OpenAirInterface (OAI) 5G [8, 9]. For

open-source Radio Access Network (RAN) implementations, there are two main options currently available. These include the OpenAirInterface (OAI) gNB, developed by the OpenAirInterface Software Alliance, and srsRAN, developed by Software Radio Systems.

1.2 Motivations and Contributions

Although software-based private 5G networks are widely used within the 5G research community, their adoption remains limited in industrial wireless applications, particularly those involving mission-critical and time-sensitive use cases. Therefore, in our ongoing work, we attempted to evaluate the performance of industrial use cases using a software-based 5G system. Through this process, we have identified several challenges and difficulties in integrating 5G wireless with industrial applications, and we observed insufficiency in latency compliance regarding time-critical use case requirements from our experimental results. This report is motivated by our experience with software-based 5G systems and feedback from the industrial wireless community.

In this report, we perform a gap analysis of 5G technical challenges for industrial applications with a focus on software-based implementations. Given the vast scope of 5G, this report focuses mainly on the challenges and opportunities related to the RAN components and in industrial deployments of 5G and beyond. To develop our perspective, we used our experience with software-based 5G networks and feedback from the industrial wireless community. Our main contributions of this report are the following.

- Summarize industry feedback on 5G challenges from wireless system integrators, developers, and device manufacturers. These insights help define research areas regarding the implementation and development of 5G services in addition to future generations of wireless technologies.
- Identify key concerns and challenges to highlight missing elements and current gaps in 5G development, particularly in software-based implementations.
- Propose potential solutions and offer insights that may serve as future research directions to address these concerns and challenges.
- Emphasize the importance of evaluating the performance of 5G subject to realistic industrial wireless physical and radio environments, reinforcing the need to support standardization efforts, such as the IEEE 3388 standard [10].

1.3 Report Organization

This report serves to analyze the challenges and opportunities for software-based 5G private networks. We primarily focus on mission-critical and time-sensitive applications. To better serve the industrial wireless community, we conducted a series of interviews with industrial stakeholders to hear their concerns with current 5G systems. We summarize their

feedback in Section 2.¹ Section 3 discusses Quality-of-Service (QoS) requirements for demanding 5G industrial applications. Section 4 discusses the latency compliance challenges associated with software-based 5G networks, and Section 5 explores the possibilities of integrating TSN with 5G. Section 6 introduces the benefits of mmWave technology in 5G and describes the difficulties associated with integration. Then, in Section 7, we discuss the impact of wireless RF aggressors and highlight the need to accurately assess the performance of industrial wireless systems. In Section 8 we describe the need for improved instrumentation and data exposure of software-based 5G networks. Finally, Section 9 concludes the report with a summary of the gaps in 5G.

2 Industrial Stakeholders Perspectives and Expectations of 5G

In this section, we identify the challenges in the adoption of 5G networks using feedback from the wireless community. As discussed in the previous section, 5G could serve as a primary role for wireless communications in the pursuit of achieving the goals of Industry 4.0 and 5.0. 5G has the advantages of high throughput, long-range coverage, robust security, mobility, and unique versatility for network configuration and QoS support. All these advantages make it suitable for use cases that require broadband connections, fixed wireless access, wireless IoT, and mobile wireless applications, including drones or vehicles.

However, despite all those advantages and potential applications, widespread adoption of 5G in many industries lags behind expectations. The use of 5G has not achieved the level of expected success. More effort should be focused on understanding the market pressures to drive the development of standards for 5G and beyond.

To understand the various perspectives of the industrial wireless community, we organized a meeting with the National Institute of Standards and Technology (NIST) Industrial Wireless Technical Interest Group (IWSTIG) [11] and the Avnu Alliance [12] to discuss the challenges of adopting 5G for industrial applications. We conducted a series of interviews with key stakeholders from industry and academia circles. We would like to acknowledge the interviewees, who are listed in the Acknowledgments section. The scope of this section is not limited to software-based 5G, and it also applies to 5G systems as a whole and other wireless communications.

We conducted these interviews to expand our understanding of the needs expressed by the industrial wireless community. With this enhanced understanding, we aim to bridge the gaps between users, technology developers, device manufacturers, and system integrators, providing directions for future development based on industry needs.

¹The interviewees from the industrial wireless community are mentioned in the Acknowledgments section.

2.1 Industrial Wireless Use Cases

The development of 5G for industrial applications should focus on supporting the network requirements of emerging applications to increase industrial wireless adoption. Industrial verticals could benefit from the increased adoption of wireless technology. The verticals include mobile robotics, process control, discrete manufacturing, and functional safety. According to our interviewees, most existing industrial wireless applications are either low data rate (for remote operation, control, IoT data) or use heavy uplink (UL) traffic (video and monitoring systems), which are usually less time-critical. Therefore, for these applications, 5G lacks a clear advantage compared to other mature wireless technologies, such as Wi-Fi, WirelessHART, Zigbee, and ISA 100.11a.

However, the advantage of 5G is that the network can be configured to meet the requirements of various use cases, giving 5G a unique potential, as described in [13]. Future 5G and beyond technology further broadens the original three main service categories: AI & Communication, Integrated Sensing and Communication, and Ubiquitous Connectivity [14]. The three additional and original service categories are shown in Figure 2.

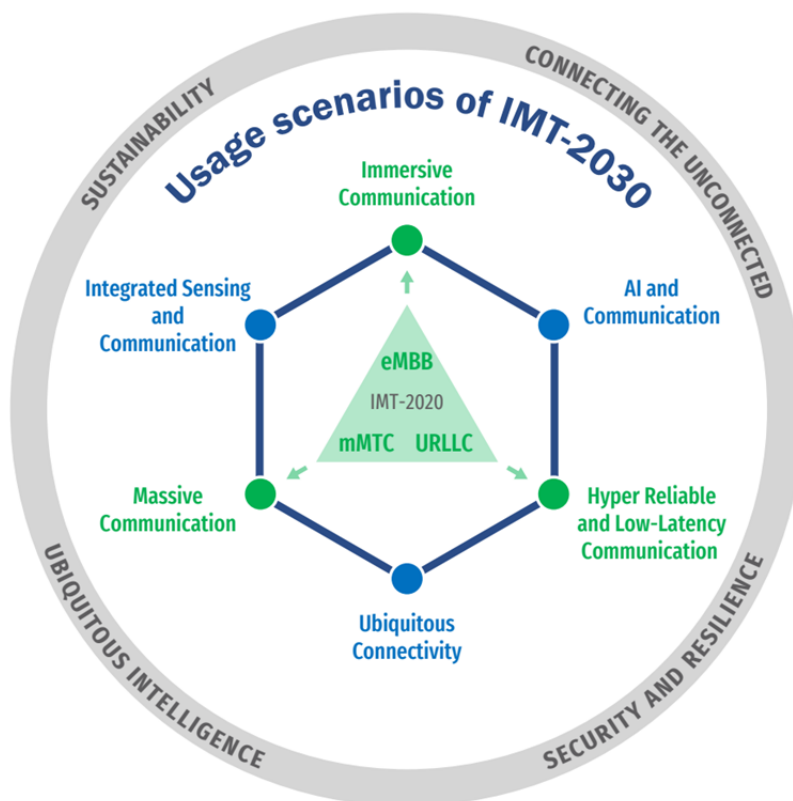


Figure 2: Usage scenario classes, or service categories, of IMT-2030, from [14].

We expect increased interest from the industrial wireless community in the next few years in the following key areas.

Time-critical Industrial Automation These applications have strict requirements for extremely low latency and high reliability. Examples include applications inside factory workcells, specifically for safety and closed-loop regulatory control.

Human-in-the-loop Control These applications have less strict latency requirements than closed-loop control, and may require high-throughput for video streams. Some examples include remote control of vehicles, robotics, and remote surgery.

Automotive Connectivity These applications include wireless Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and the more general Vehicle-to-Everything (V2X). All these types of vehicle connectivity enable an ecosystem for vehicles to exchange real-time information with their surroundings—improving road safety, autonomous driving, and traffic optimization.

Public Safety and Disaster Response These applications require reliable communications between first responders and other relevant agencies during emergencies. The continued development of non-terrestrial networks and sidelink communications in 5G-advanced can provide support for challenging environments when there is a lack of sufficient infrastructure.

Professional Audio/Visual (Pro AV) with Multimedia Pro AV with specialized audiovisual systems is regarded as an emerging use case with increasing potential. Pro AV has high-bandwidth and strict QoS demands for downlink (DL) and UL, which are used for AV control, camera traffic for streaming and monitoring, and human detection with data processing. The high throughput, low latency, and slicing features also support Extended Reality (XR) functions, which is a popular target use case for 5G and beyond.

Predictive Networking AI has applications for analyzing, predicting, and optimizing network performance as well as user experience. There are targets for the 3GPP in 6G development that outline an architecture with AI-native networking to predict network events with self-optimization. Integrated Sensing and Communications (ISAC) and cognitive digital twins are emerging approaches for network state prediction, capable of mirroring and predicting real-world events in real time.

2.2 Challenges of 5G Adoption from the Industrial Wireless Community

In this subsection, we summarize the major challenges in the adoption of industrial 5G which we discussed with the industrial stakeholders during the interview process.

Market Benefits and Returns

The most important factor for 5G adoption in a multitude of industries is whether the technology can be linked to market benefits and returns. High costs may hinder indus-

trial users from deploying 5G systems. As mentioned in the previous section, 5G offers no clear advantage for traditional, low-data rate, wireless use cases, making other wireless technologies more preferable when cost is the main consideration.

In addition, there is a low realization of advanced technologies discussed in the 3GPP standard that are implemented into actual 5G systems, specifically URLLC features for industrial applications. Current industrial devices do not meet the latest specifications of the 3GPP standard, however, the 3GPP working group continues to publish more advanced features. The gap between standards and device availability is a concern within the industrial wireless community.

Most importantly, industrial use cases are quite different between use case areas due to the nature of their corresponding RF environments and traffic types, making customized network deployments and advanced equipment necessary. Even though 5G networks can be versatile and flexible due to softwarization and virtualization features, specialized devices and daughter card support on the User Equipment (UE) side are still required. However, advanced and customized communications equipment is a smaller market, leading to less incentive for manufacturers to invest in those products. Therefore, for manufacturers to have the incentive to create 5G products that meet industrial communications requirements, they must experience market pressure. It appears manufacturers are not certain what the future market holds, thus, the implemented functionalities of wireless devices are lagging behind standardization efforts. Many of these future industrial applications will require a robust communications system to be implemented first before widespread adoption occurs. There is a gap between manufacturers and users that must be bridged to enlarge the 5G and industrial wireless markets.

System Development and Management

Industrial wireless systems have specific challenges associated with system development and management. We describe how these challenges arise between users, technology developers, and device manufacturers. With input we collected from industrial community, we present the following challenges.

Complexity Highly complex cellular systems are a main concern for 5G users and network integrators. The multitude of configuration settings required by 5G networks results in increased difficulty in deployment and management. Packet transmission latency may suffer due to many supported features and processing times of the connection between protocol layers, which is discussed further in Section 4. 5G offers flexible system configuration, which, in practice, increases the degree of complexity in the control and management functions of the network. From the user's perspective, an easily manageable system that can achieve the required network performance is desirable, whereas the development of 5G appears to be moving in the opposite direction by the addition of more complex features. The industrial community has concerns about this complexity, and desires fewer configuration options to facilitate

simpler deployments. If complexity remains high, industry may be forced into acquiring network managing services from third party companies (this may raise security concerns) or heavily invest in personnel training.

Interoperability The industrial wireless community stressed that the interoperability challenges between mainstream IP networks and 5G networks hinder adoption. Routing between IP networks and 5G networks adds increased difficulty for private deployments. We have heard and experienced interoperability issues in routing when an application uses dynamic IP and port information. The level of complexity of 5G standards and the various implementations from multiple vendors creates interoperability challenges between 5G and legacy networks. For example, integrating TSN with 5G poses a challenge due to difficulty with integrating existing IEEE 802.1 TSN standards with 5G, and this aspect is discussed further in Section 5.

Standards Development and Available Product Support As mentioned earlier, the standards are ahead of features implemented into the latest available 5G products. Device manufacturers hesitate to make products implementing specific features due to high cost and relatively smaller market. However, from the viewpoint of system integrators, they want to observe and validate real hardware implementations rather than only relying on studies and simulations. mmWave and URLLC are examples of features that industry has yet to successfully implement due to the lack of validation and product availability. Moreover, industry traditionally prefers long-life cycle products, and the rapid progress of 5G technology towards 6G becomes another concern for adoption. Some members of the industrial wireless community hesitate to adopt 5G, as they expect the rollout of 6G in the next few years.

Exposure of Management Parameters and System Control Determining the level of exposure of management parameters in control systems has always been a challenge for manufacturers. End users generally do not want to configure highly complex network management features. However, researchers and technology developers desire to have access to many parameters in the wireless stack. We learned in our interviews that the configurable parameters of chips or devices must be more fine-grained and accessible in order to experiment with tunable features and measure performance. From the manufacturer's perspective, practical considerations tend to align more with the users—not just from a market standpoint, but also because partially limiting the level of control can greatly reduce the risk of users disrupting operations.

Developing Trends and Time-critical Applications Another challenge to 5G development is the conflict between technology trends and low latency requirements from time-critical applications. The current trend for 5G is more towards the ideas of virtualization, cloud-based, and software-defined networking. As a result, the whole network may become more complicated and disaggregated, introducing more layers, adding to latency and adding interoperability challenges.

To address these challenges, some members of the industrial wireless community suggested that more effort should be put into establishing effective communication between users, technology developers, and manufacturers to identify common ground, which will aid development for next-generation industrial wireless technology.

Functional and Intrinsic Safety

Another challenge for 5G adoption is meeting the requirements for functional safety and intrinsic safety use cases, especially in industrial control and automated systems. Functional safety is required for safety-critical applications, for which the 5G network should ensure a reliable and secure medium to maintain system safety in the event of failures. However, we have heard from industry stakeholders that users interested in deploying a wireless system often struggle to achieve desirable network performance for functional safety due to lack of understanding of RF and wireless propagation, specifically when encountering interference challenges and in finding products that meet their needs. In addition, the wireless channel has intrinsic challenges to overcome, which we discuss in detail in Section 7.

Intrinsic safety in wireless communication is another area that is often overlooked. Intrinsic safety refers to a design approach and protection methods that ensure electronic and wireless devices are physically protected against hazardous environmental conditions such as ignition, dust, explosions, or radiation. Intrinsic safety is required in many industrial use cases where flammable gases, dusts, vapors, or fibers may be present, such as in oil refineries, chemical plants, and mining facilities. With regard to wireless communications, the RF power levels and intrinsic safety requirements must comply with certain standards, which vary around the world, adding an extra barrier to adopt wireless. From the perspective of manufacturers, the cost and difficulties associated with product design are barriers due to the need for the certification of specially designed enclosures. From the perspective of wireless end users, they not only face the need to invest in more expensive equipment, but they also find difficulty in finding certified products.

Interference and Validation Metrics

In 5G, various techniques have been proposed to mitigate the impacts from RF interference and multi-path effects including the placement and direction of antennas, Multiple-Input and Multiple-Output (MIMO), beam steering, channel hopping, multi-cell or super-cell implementations, and reconfigurable intelligent surfaces. However, these techniques are either in the development stage, or current implementations cannot guarantee performance in dynamic industrial environments. As a result, we heard the community express the importance of conducting standardized benchmark and prototype tests to evaluate the performance of wireless systems and emerging technologies under realistic industrial environmental conditions. We further discuss interference and propagation hurdles in industrial environments and evaluation processes in Section 7.

2.3 Expectations and Future Needs

In this subsection, we summarize the industrial community's expectations and future needs for 5G and next-generation wireless technologies. For the industrial wireless community to adopt 5G, the following topics should be addressed.

Bridging the Gaps Between End Users, Technology Developers, and Manufactures of 5G Products

Currently, the development of 5G is not aligned with the needs of the industrial market, and there are fewer products available that support new features. Moreover, the lack of confidence in wireless for industrial use cases prevents the growth of industrial 5G adoption. Therefore, to support adoption, the 5G community should bridge the gaps between industry stakeholders and standardization groups. By doing so, end users, technology developers, and manufacturers can gain a greater understanding of requirements and find common ground.

Future Developments and Expectations for 5G and Beyond

The most frequently requested needs from 5G end users can be summarized into two aspects. From a system development perspective, future 5G networks need a user-friendly design for network configuration. We heard from the interviews that the 3GPP standards are overly complex and the simplification and distillation of features could better serve industrial wireless applications. Currently, 5G has a plethora of features that are not applicable for many private deployment use cases. The other expectation is increasing support for more useful features in actual devices. Some of these useful features that were discussed by the industrial community include multi-cast, 5G-TSN, enhanced 5G to Ethernet support, Sidelink, and URLLC with sub-millisecond delivery.

Spectrum Regulations

Currently, the 5G spectrum is fragmented and lacks unified regulations across the world. The lack of spectrum regulation alignment on a global scale poses challenges for device compatibility, interoperability between infrastructure and UEs, and the manufacturing of devices. In addition, new available bands that are less crowded are needed to mitigate the interference impacts on wireless communications. Although 5G standards include 24-52 GHz FR2 mmWave bands, support is not widely available, making this band an infeasible solution for many use cases. The 7-24 GHz FR3 band supports higher throughput capacity than the sub-6 GHz FR1 band with fewer downsides compared to the FR2 band, specifically for propagation loss and manufacturing requirements. Thus, the FR3 band is a reasonable band to target for future spectrum allocation regulations for 5G and beyond systems.

Testing and Evaluation Metrics and Methods

Standards for testing and evaluation metrics and methods are essential for industrial wireless stakeholders. Device manufacturers should utilize performance and evaluation standards to test features in wireless systems so they can validate performance in the intended RF environment. System integrators and end users also need standardized metrics and benchmarks to verify whether the system will support the QoS requirements for the desired use cases. More details on a standardization effort to assess wireless performance is described in Section 7.

3 Industrial QoS Challenges for 5G Deployment

The target use cases for mobile communication technology have evolved significantly with the advent of 5G. Despite the fact that previous generations of cellular technology served mainly for generic communications and data, 5G has expanded to private industrial deployments and was designed to accommodate diverse traffic. 5G use cases span various industry verticals, including manufacturing, automotive, gaming, smart cities, healthcare, etc. [13, 15]. Each use case involves different types of traffic, each with unique QoS requirements. Consequently, configuring and deploying 5G networks to meet these QoS requirements is a challenge.

The 5G standard implements QoS using a two-level packet filtering mechanism, as defined in 3GPP 23.501 [16]. When an IP packet enters the 5G network, the 5G core's User Plane Function (UPF) or the UE classifies packets into QoS flows based on packet detection rules, and then, these QoS flows are mapped to "data radio bearers" between the UE and gNB for over-the-air transmissions using predefined QoS profiles. Each type of traffic is assigned a 5G QoS Identifier (5QI) value, which serves as an indicator to represent the QoS level. Although the 3GPP 5G standard provides a QoS mechanism and defines example services for some 5QI values, several challenges remain for 5G systems implementing end-to-end QoS for industrial applications.

3.1 Standardizing QoS Profiles for Industrial Applications

Understanding the QoS requirements of existing traffic is important when deploying a 5G network, as it allows the user to plan and prioritize mission-critical traffic. The NIST AMS 300-8 report produced wireless user requirements for factory workcells for a range of application classes—with the most strict requirements being for safety applications and the least strict for condition monitoring [17]. It outlined key parameters such as latency, reliability, range, scale, payload size, and update rate for the various traffic classes. However, the report focused specifically on factory workcells, whereas 5G applications extend to a wider range of use cases, which are continuously evolving. QoS requirements can also differ within the same traffic class due to different usage needs. Finding a universal QoS profile that fits all use cases and service classes is challenging, which triggers the need to create reference profiles tailored to numerous use case classes. We see the value in standardizing various QoS profiles for the vast range of industrial applications.

3.2 Challenges with the 3GPP 5QI Table

For a 5G network to successfully deliver the appropriate QoS information, it is necessary to assign 5QI values to QoS flows. This allows network operators to configure appropriate 5QI values and is beneficial for system integrators as it creates clear performance goals for various use cases. However, a direct mapping is missing that links existing 5QI values

and low-latency and high-reliability industrial traffic types. The lowest packet delay budget for existing 5QI tables is 5 ms with a corresponding packet error rate (PER) of 10^{-5} . It is challenging to find a direct map between the 5QI entries and application-level QoS requirements. Functional safety and real-time motion control for industrial applications may require PER as low as 10^{-7} with 4 ms of latency to ensure fewer than one failure in 1000 years of operation—which is a typical requirement for many industries [17]. To address the needs of industrial applications, the 5QI table should be expanded with more applicable and standardized values for industry, or more effort should be put on the layers above the network layer to achieve application’s QoS requirements.

3.3 Creating Delay Profiles

To create an effective network deployment, one should be able to accurately estimate the per-hop delay between all network contributors, which is beneficial for planning, dimensioning, and configuring the network. It is challenging to accurately estimate the latency associated with software-based 5G systems for industrial applications due to uncertain processing delays, dynamic channel conditions, and the lack of device instrumentation. Therefore, comprehensive testing and measurement methods are needed to evaluate end-to-end performance and the latency of the RAN. These aspects will be further explored in Section 4, Section 7, and Section 8.

4 Latency Compliance Challenges

Maintaining low-latency communications is a main target of many industrial wireless networks. 5G's URLLC feature is undoubtedly what makes 5G an attractive technology for wireless solutions, especially the sub-millisecond delay aspect. When comparing 5G with LTE, 5G was developed with greater configuration flexibility to lower latencies. The latency targets defined by 3GPP 38.913 [18] are below 1 ms for URLLC and 4 ms for eMBB, which are suitable targets for the requirements of time-critical use cases such as closed-loop real-time control or safety. However, it is challenging to achieve these goals in actual deployments due to unpredictable environmental and channel conditions. The challenge is even greater when using a software-based 5G system, especially for UL traffic, where we observed a typical end-to-end latency on the order of tens of milliseconds. For example, according to the test results from our previous work [19] using a 5G testbed deployment, which is recreated here in Table 1, the average delays of the UL and DL Time Division Duplex (TDD) schedule configurations were significantly higher than the requirements of the 3GPP standard. The previous work emulated an industrial traffic stream, by transmitting UL and DL traffic concurrently and it presented the end-to-end delay with various Time-Division Duplex (TDD) schedules. The minimum mean delay, μ , for the UL traffic was 12.5 ms and the DL was 5.5 ms. The high latency standard deviation values, σ_τ , raised concern in the pursuit of deterministic communications, which many industrial use cases require. Similarly, a study by National Institute of Standards and Technology on an Open Radio Access Network (O-RAN)-based 5G testbed using a srsRAN gNB [20] reported an average of 20-40 ms of delay with PING testing. Another study on an OAI-based 5G network [21] observed an end-to-end delay of 20-30 ms within the URLLC slice.

Typically, the end-to-end latency of packets includes delay from the IP data network, the 5G core network, and the 5G RAN. For most private 5G network use cases, the latency in the 5G core network can be negligible compared to the latency from the access network, given that the core network or the UPF is typically located on-premises at the users' site. The close proximity of the core reduces latencies associated with large-scale cellular 5G networks. Delays introduced from the IP network are outside the scope of this report, as these networks are not 5G-based. Therefore, we focus on the challenges of achieving low latency in the RAN and UE planes with a software-based 5G system.

4.1 Sources of Latency in the Radio Access Network

In [23], Håkegård et al. presented a performance analysis of 5G RAN latency using round-trip times. They analyzed latency sources in a software-based 5G system as the packets traversed the network. Here, we identify additional factors that affect latency in a software-based 5G implementation. Figure 3 shows the latency sources that we identified as key contributors that increase communication delays for the RAN. This allows us to propose potential solutions for each component that contributes to latency.

Table 1: Latency Summary from 5G Testing

TDD	UL MFI	No. Vid.	Dir.	μ	σ_τ	Min.	Q1	Med.	Q3	Max.
3-1-1	0	1	UL	13.178	4.845	4.837	10.398	12.497	14.983	67.543
3-1-1	0	1	DL	5.743	0.634	4.168	5.321	5.857	6.093	10.416
3-1-1	0	2	UL	16.646	48.957	4.512	10.453	12.654	14.723	926.723
3-1-1	0	2	DL	5.778	2.409	3.905	5.131	5.966	6.226	134.322
1-1-3	0	1	UL	13.797	31.248	4.078	9.977	12.205	14.207	936.114
1-1-3	0	1	DL	5.874	2.090	3.905	5.182	5.432	6.204	133.559
1-1-3	0	2	UL	17.483	13.460	3.958	10.455	12.821	15.741	92.248
1-1-3	0	2	DL	5.772	0.840	3.309	5.352	5.498	5.656	15.606
3-1-1	1	1	UL	15.193	10.182	4.468	10.459	12.689	15.467	82.798
3-1-1	1	1	DL	5.510	0.665	3.309	5.001	5.407	6.004	14.284
3-1-1	1	2	UL	12.457	2.783	5.292	10.241	12.381	14.518	28.371
3-1-1	1	2	DL	6.290	0.526	0.703	5.841	6.292	6.729	15.761
1-1-3	1	1	UL	14.069	31.869	3.754	10.174	12.293	14.612	932.660
1-1-3	1	1	DL	5.868	2.069	3.356	5.256	5.449	6.621	137.375
1-1-3	1	2	UL	16.708	53.800	4.639	10.183	12.360	14.340	1009.459
1-1-3	1	2	DL	5.591	2.388	4.344	5.063	5.262	5.462	133.655

Latency performance in milliseconds from a software-based 5G testbed, recreated here from our previous work, in [19]. The TDD Schedule indicates the slots for downlink (DL), shared link (SL), and uplink (UL); UL MFI indicates UL maximum frame inactivity; No. Vid. indicates the number of video streams simultaneously active; and the Dir. indicates the measured UL or DL communication direction. Other statistical information regarding the latency is displayed.

The Processing Delay Between Protocol Layers

The processing delay in this context is the time for the gNB or UE to perform data processing and control signaling between layers in the protocol stack before scheduled packet transmission and after packet reception. To decrease the processing delay, systems should have ample computational resources, especially for the software-based 5G network running on a virtual RAN (vRAN). In a vRAN, all computationally intensive baseband processing functions—especially for digital signal processing implementations—are performed using general-purpose computing devices, rather than specialized hardware. Therefore, the processing power of the RAN can easily become a limiting factor in achieving the desired latency budget. System integrators should determine the appropriate computing resources required to ensure minimal latency impacts from the utilized hardware.

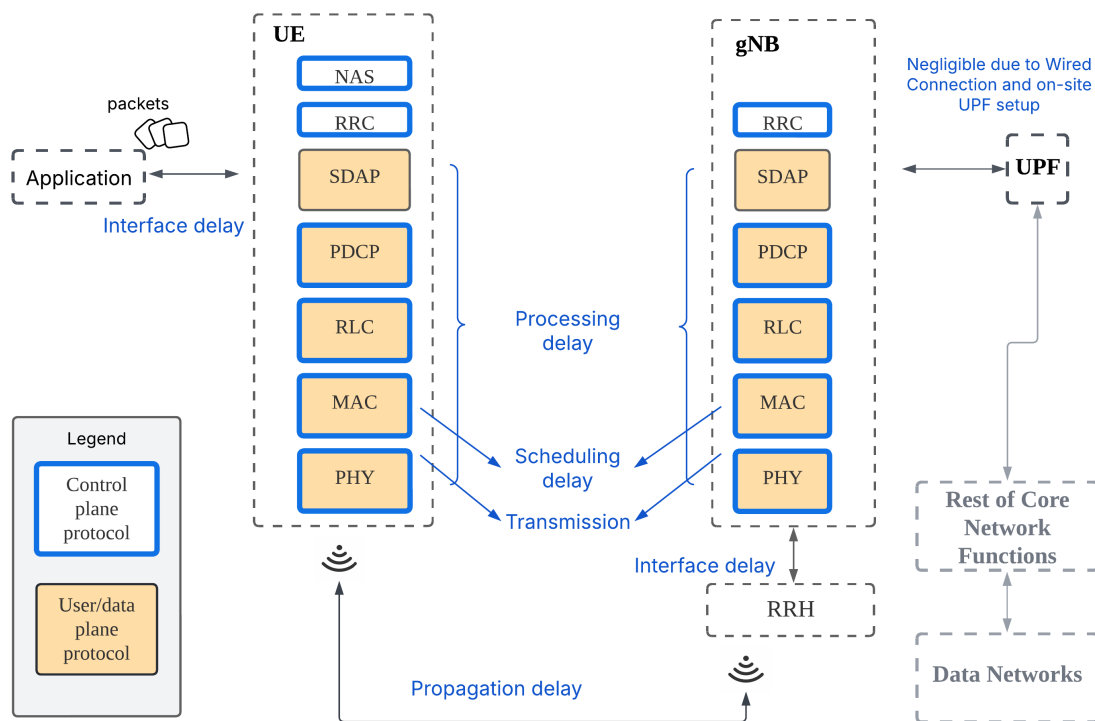


Figure 3: The primary latency sources, shown in blue text, for packet transmission in a software-based 5G RAN architecture. Various protocol layers in the UE and gNB are shown as function blocks (NAS, RRC, SDAP, PDCP, RLC, MAC, PHY). More details of these protocol layers are described in [22].

Scheduling Delay

Scheduling Delay is the time it takes between when the data is ready to be sent and when it is actually transmitted over the air. Packets need to be queued until available time slots are assigned. The two main factors that affect the scheduling delay are the physical scheduling structure and resource allocation schemes.

The latencies of transmitted packets are highly dependent on the physical scheduling structure defined in the time domain. While the 5G scheduling mechanism is similar to that of LTE, it offers greater flexibility and finer granularity, enabling the possibility of lower latency and higher resource usage efficiency. The support for multiple NR numerology (i.e. Sub-Carrier Spacing (SCS) in 5G) allows for smaller symbol durations, reducing the Transmission Time Interval (TTI) as low as 15.625 microseconds using a 960 kHz SCS. Additionally, various scheduling types and structures in the time and frequency domain enable the network to assign resources with high degrees of freedom up to symbol-level granularity.

A minimum scheduling delay exists even when sufficient bandwidth is available in a given resource allocation scheme. Håkegård et al. described the inherent scheduling latency, especially for the UL scenario, since a grant is required from the gNB for an UL

packet before it can be scheduled [23]. In addition, for the case when multiple UE devices compete for limited bandwidth, an additional queueing delay is added. The scheduler serves to allocate time slots within the limited spectrum to meet QoS requirements or to achieve power efficiency [24]. Various resource allocation schemes and advanced queuing algorithms were proposed to remedy queuing delays to optimize performance, presented in [25].

Transmission and Propagation

In most industrial use cases, propagation delay can be negligible, due to relatively short transmission distances, which adds delays on the order of 10's to 100's of nanoseconds. Transmission delay, which is the time for a packet to be transmitted successfully at the physical layer, cannot be neglected. Continuous retransmissions triggered by packet data errors can significantly impact latency and reliability. This issue becomes even more critical in industrial environments, as industrial channel conditions are typically harsh, which is described further in Section 7.

Additional Interface Delays

In our findings from experiments with a software-based 5G testbed, we observed additional delays arising from two locations: one at the 5G chipset on the UE devices and the other at the connection between the RAN and the radio unit (RU). The former is an additional delay observed from the link between the 5G interface and the application layer, and the latter is caused by RU interfacing with the gNB system. These delays, approximately in the millisecond range, may be undetectable in many use cases, however, they become significant in URLLC use cases that require sub-millisecond latency.

Other Delays

Some other delays include synchronization, connection handling and handover, etc. Although these delays do not occur regularly, they can still degrade connection resiliency.

4.2 Delay Challenges on a Software-based 5G Network

Based on our experimental results and the review of related work, it is difficult to achieve the low-latency targets defined by 3GPP for current software-based 5G systems. The 4 ms latency target for eMBB and 1 ms for URLLC are targets defined for small packets, and we could not match these targets using our system. Here, we identify key challenges in achieving low latency in software-based 5G networks, and we propose possible optimization directions.

Processing Delays from Hardware Limitations

In a software-based 5G implementation, network functions are installed and run as software on commercial off-the-shelf hardware. Therefore, the computational speed of the hardware imposes a virtual ceiling on overall latency performance. Furthermore, general-purpose CPUs are not optimized for real-time radio signal processing, which introduces more latency than what is added by dedicated 5G hardware. Implementing all RAN functions in software may introduce additional jitter, which is harmful for time-sensitive applications that require deterministic latencies.

At the physical layer, there is an implicit processing constraint that is the cause of additional latency. Due to limitations on processing speed, the scheduler will need to allocate resources a few slots ahead to allow for sufficient preparation time, such that the scheduled packet transmission time will align with the start of the transmission window time. For example, if the 5G gNB scheduler needs to allocate resources 3-4 slots ahead of the actual air time, this introduces an inherent 1.5 to 2 ms of delay when using a typical 30 kHz SCS, which was the most commonly used SCS in the FR1 mid-band. Theoretically, under this condition, achieving URLLC's sub-millisecond latency can only be feasible in the FR2 band due to the shorter slot durations. However, this is impractical since most 5G devices do not support millimeter wave (mmWave) transmissions.

Possible solutions to processing limitations include hardware upgrades, software optimization, or hardware acceleration. Hardware upgrades, whether it involves replacing the RAN with higher-performance computing hardware or upgrading devices to support mmWave, presents a dilemma—inevitable cost increases of 5G systems. One of the biggest advantages of software-based solutions is the relatively low cost compared to vendor-specific hardware packages, along with the accessibility of off-the-shelf computing hardware. Continuous hardware upgrades will gradually lose the cost advantage. Hardware acceleration is a more feasible solution for enhancing performance with existing computing resources. Hardware accelerator components include graphic processing units (GPUs), data processing units (DPUs), and FPGAs. Process acceleration at the physical layer can offload work from the CPU. Disaggregating the RAN and implementing a different functional split may be advantageous. Utilizing disaggregation with compute-intensive network functions on different machines will decrease the workload on each machine. Implementing a functional split at the gNB that puts additional radio processing functions onto the RU hardware rather than the baseband unit can reduce the processing burden on the baseband unit.

Delay Monitoring Tools

To measure delay, accurate timestamps should be recorded at each node, both at the application layer and between various 5G protocol layers. For open source software-based 5G networks, measuring delay inside the gNB protocol stack can be challenging. Open source software developers focus more on technology realization and verification rather than internal performance assessment. Though there are few solutions proposed [26, 27],

all of them have disadvantages. For example, these tools either impose more demanding hardware requirements or introduce additional overhead and delays. We discuss the gaps in instrumentation and measurement further in Section 8.

Validation and Testing over Real-world Deployments

Extensive research exists that discusses various scheduling schemes which aim to meet the QoS and energy requirements, like in [25], and most mechanisms have been validated through simulations, rather than real-world deployments. As a result, potential hidden latencies in practical implementations may remain undiscovered due to discrepancies between simulation models and actual hardware. Moreover, wireless communications in industrial environments presents unique challenges due to harsh and dynamic channel conditions. Validating network performance in such contexts requires testing subject to realistic scenarios that involve fluctuating signal strength, increased packet retransmissions, and various sources of interference. This highlights the importance of 5G testbeds which are capable of evaluating various network configurations and designs using real devices in a realistic RF environment. More details on channel recreation and testing will be discussed in Section 7.

Network Resiliency

Network resiliency is another crucial factor regarding latency. The ability to recover quickly from disruptions and disconnections is critical. However, in software-based 5G networks, UEs may take longer to reconnect after a disconnection, which is a common issue with poor channel conditions. In some cases, restarting the wireless adapter is required to restore connectivity. Further standardized testing subject to industrial RF environments could serve as the input needed to increase the resiliency of software-based 5G networks.

Available Technology in the RAN and UE

Stakeholders in 5G have proposed various techniques in the effort to reduce latency. For example, different 5G numerology related to higher SCS values can be used to achieve much shorter data symbol durations in transmission. Moreover, self-contained slots, mini-slots, the code block group concept, and different HARQ techniques were proposed to decrease transmission time and increase data reliability. In addition, grant-free UL transmission can also greatly reduce the UL scheduling time. In summary, short symbol duration, faster acknowledgment mechanisms, lower retransmission and scheduling latencies are key avenues in achieving URLLC. However, these methods may not be supported by all networks or UEs. Traditionally, industrial implementations lag behind technology development. A representative example is that 5G technology was developed and implemented before 2020, yet the first UE chips for many private 5G devices were only made widely available in 2023 [4]. As mentioned by the industrial wireless community in Section 2, more

work should be done in delivering low-latency products using the latest developments in the 5G specification.

5 5G with Time-Sensitive Networking

The industrial wireless community has expressed their interest in utilizing time-sensitive networking (TSN) technology, which serves an important role in industrial communication, where reliable and real-time data transmission is essential for industrial automation (Industry 4.0) and human-machine collaboration applications (Industry 5.0 or tactile networks) [28, 29]. However, at this time, 5G-TSN is far from being widely implemented. This section introduces how 5G-TSN works at a high level and discusses the current challenges of implementing 5G-TSN.

5.1 Wireless TSN and 5G-TSN

TSN is a set of networking standards defined by the IEEE 802.1 working group to ensure deterministic and reliable delivery of time-sensitive data over Ethernet networks. These standards can broadly be categorized into four main areas: time synchronization, bounded low latency, ultra-reliability, and resource management. Implementing existing TSN standards over wireless communications was shown to increase determinism in [30]. Major TSN development groups are targeting Wi-Fi and 5G to integrate TSN features in the wireless domain. Comprehensive overviews of TSN and its wireless extensions were published in white papers by members of the Avnu Alliance in [12]. Although Ethernet-based TSN has been established for almost a decade, wireless TSN development remains in the early stages. The transition to wireless communications introduces various challenges, and only a subset of TSN features were implemented and experimented with over wireless environments.

Starting with 3GPP Release 16, the 5G standard introduced an architecture to support TSN integration. Figure 4 illustrates the network architecture and key network functions involved in the integrating 5G with TSN. Within this framework, the 5G system functions as a logical wireless bridge within the greater TSN network, delivering time-sensitive packets according to TSN schedules. The scheduling for data transmissions are defined by the Centralized Network Controller (CNC). The CNC receives information from the Centralized User Configuration (CUC) and end devices to calculate the optimal transmission schedule. Three primary network functions, as shown in the yellow blocks in Figure 4, enable 5G-TSN integration as follows.

- The Network TSN Translator (NW-TT) and Device Side TSN Translator (DS-TT) serve as the interfaces to TSN bridges at the 5G core (5GC) and UE devices. These translators manage time synchronization using Precision Time Protocol (PTP) packets and handle configuration management to ensure proper traffic routing and processing.
- The TSN Application Function (TSN-AF) interfaces with the TSN CNC, which maps TSN schedules to 5G QoS policies.

In summary, 5G can be viewed as a black box inserted into a TSN network, where the mentioned network functions work together to synchronize timing information, calculate

the remaining delay budget for TSN traffic, and ensure timely packet delivery according to TSN scheduling by using 5G's own QoS handling policies and techniques.

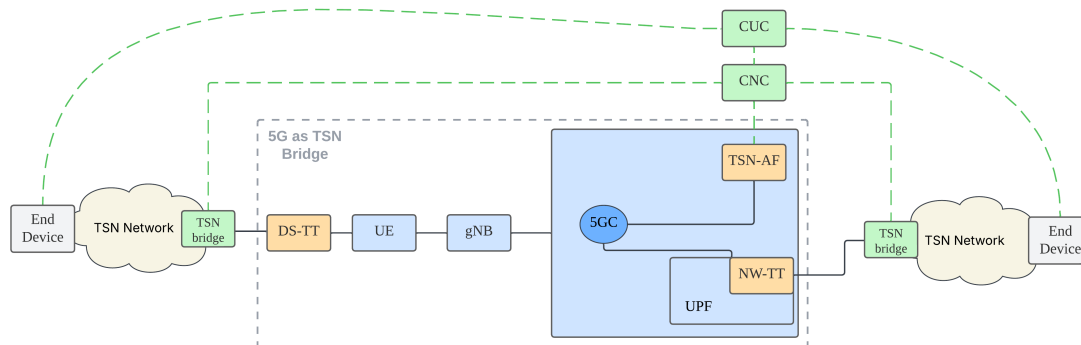


Figure 4: Network architecture of integrating 5G system into a wired Time-Sensitive Network (TSN).

5.2 Challenges of Deploying 5G-TSN

Currently, wireless TSN technology is still in its early stages, with vendors gradually developing devices that support various TSN capabilities. Different solutions are emerging, including modems with built-in TSN support and software-based TSN prototypes for client devices. However, most advancements and tools for wireless TSN are primarily validated through simulations. Real-world deployments and testing are currently limited to small-scale demos in testbeds and laboratories. Field trials are also needed in the development of the technology, with increased adoption likely in the next few years.

Complexity of 5G-TSN

According to feedback from TSN developers and integrators, the main challenges of 5G-TSN stem from the inherent complexity of 5G systems and the difficulties associated with performing representative experiments. From the perspective of 5G-TSN developers in the industrial wireless community, the biggest challenge is establishing testbeds with measurement capability that incorporate all the components (gNB, Core, end devices, and TSN Translators on both sides) to accurately measure end-to-end performance. Compatibility between network components from different vendors is challenging as each vendor typically runs proprietary software. This lack of transparency stifles integration, making the integration of 5G-TSN significantly more challenging. Using open-source software allows researchers to increase transparency and collaborate with stakeholders interested in 5G-TSN.

Moreover, the complexity of configuring and managing 5G networks adds another layer of difficulty to deployment. These difficulties are not only applicable to 5G-TSN, but also

5G development. According to the expectations of the industrial community, they stressed the need for a simplified 5G standard, which would reduce the level of complexity of 5G-TSN.

Meeting QoS requirements with Software-based Implementations

The TSN bridge is where the gate-controlled list, schedule, is implemented, shown in Figure 4. Transitioning from a wired TSN network to a wireless TSN solution can be achieved through hardware or software-based implementation methods. In a similar method to other applications, software-based solutions offer greater convenience and flexibility compared with hardware. For example, TSN capabilities can be realized by adding TSN gate control to existing network queues through supported modems for 5G-TSN. However, software-based solutions introduce additional overhead to the software stack, shown in [30]. This overhead can increase the uncertainty and latency of packet transmission. Careful consideration and additional efforts are necessary when designing the TSN schedule to account for these delays and uncertainties.

Another challenge of 5G-TSN is the inherent speed of the 5G network. 5G-TSN relies on the URLLC capabilities of 5G to meet TSN requirements using its own QoS management. While not all TSN applications demand sub-millisecond latency, it remains challenging for a software-based 5G network to meet deterministic timing requirements below 10 ms, as discussed in Section 4, required by many industrial time-critical use cases.

In summary, adoption of 5G-TSN requires understanding the complexities of 5G system deployments, increasing availability of supported products, validation and testing using real-world deployments, and reducing uncertainty and delay in software-based implementations. Additionally, the current role of 5G systems in 5G-TSN is that 5G serves as a logical bridge. This bridge adds another layer of delay and creates interoperability concerns. To unlock the full potential of 5G-TSN, future standards could specify the integration of a built-in traffic scheduling capability that implements TSN features directly within the 5G scheduler at the gNB and UE. We propose that validating 5G-TSN through real-world use cases is essential to support market needs and support widespread deployments.

6 5G Millimeter Wave

The section reviews the benefits and challenges associated with deploying mmWave-based communications with 5G and beyond technology. These challenges primarily consist of limitations due to the physical nature of mmWave frequency bands. The benefits of mmWave are primarily the lack of interference and the large available bandwidth. We then discuss challenges to manufacturing, Non-Line-of-Sight (NLOS) RF channels, cost, support, and unified regulations.

6.1 Benefits of 5G mmWave Technology

The adoption of mmWave technology in wireless communications has gained significant interest in recent years, as it is gaining interest for use in 5G and other wireless networks [31]. The 5G standard incorporates the FR2 band, consisting of frequencies from 24.25 GHz to 71.0 GHz, to support mmWave transmissions. An advantage of using mmWave is its ability to support high-bandwidth, low-latency data delivery. Due to the larger bandwidth at mmWave bands, significantly more data can be transmitted compared with the lower frequency bands. In the 5G FR2 band, the maximum carrier bandwidth reaches 400 MHz, whereas the 5G FR1 band is limited to 100 MHz. Additionally, the higher numerology support at mmWave bands results in shorter symbol durations, which reduces latency and enables more symbols to be transmitted within a fixed period. The ultra-fast bitrate and low end-to-end latency makes mmWave ideal for various industrial applications requiring high data capacity and URLLC. Some key use cases for 5G mmWave may include industrial automation, virtual reality, and augmented reality.

Another benefit of mmWave is that the frequency spectrum is less used and “cleaner” compared with the lower-frequency bands. A significant portion of the spectrum remains unoccupied, and there are fewer regulatory restrictions. Radio Frequency Interference (RFI) is also significantly lower in the mmWave range. Since existing communication protocols and devices have not adopted mmWave, there is less interference between external communication networks. Furthermore, the impact of broadband noise is minimized, as high-frequency signals experience rapid fading, leading to a faster decay of the noise strength.

Lastly, the highly directional nature of mmWave offers additional benefits. The ability to integrate more antenna elements into an array enables higher gain and narrower beamwidths, facilitating improved spacial multiplexing and multiple access techniques. With more concentrated power, reduced inter-beam interference during transmission, and improved spacial diversity, mmWave is expected support higher user densities. Moreover, mmWave is considered to be more secure, as its inherently narrow beams make signal interception more challenging.

However, despite its many advantages, mmWave has not been used extensively in the industry. The most direct reasons are its high cost and limited demand for ultra-high bitrate applications for industrial use cases. In addition, mmWave communications face inherent

technical limitations. The following section outlines the key challenges hindering the adoption of mmWave in 5G industrial applications.

6.2 Challenges for Adopting mmWave for Industrial Applications

5G over mmWave bands has proved its potential as a technology for a high-throughput solution, but challenges remain for widespread adoption by industry. Here, we identify some major challenges based on the insights from mmWave developers and testers:

Manufacturing Challenges

The physical dimensions associated with mmWave devices are much smaller compared with traditional microwave-based devices, posing stricter requirements on precision manufacturing with tighter tolerances on cables, antennas, and RF connectors. A small deviation in waveguides can significantly degrade signals, leading to increased design and manufacturing complexity. The same challenges also apply to device characterization and calibration, further increasing the cost.

Device Cost and Support

As mentioned earlier, the cost of mmWave devices is already relatively high due to complex design manufacturing processes. The limited number of available off-the-shelf mmWave components further drives up costs, as few manufacturers produce these products. The high cost of mmWave equipment hinders market interest, as current microwave-based devices are sufficient for many use cases. The vicious cycle between supply and demand poses one of the greatest challenges in mmWave adoption. However, as new use cases emerge needing higher throughput and a "cleaner" transmission band, adoption will follow.

Impact from Channel Degradation

The short wavelengths of mmWaves cause elevated signal decay, due to propagation loss and absorption, and significantly impact signal reflection and diffraction characteristics. Data transmissions can be severely degraded when obstacles in the environment block the LOS path. These challenges are even more pronounced in industrial environments, where NLOS scenarios and poor channel conditions occur more frequently due to clutter, highly-reflective objects, and multi-path effects, which are discussed further in Section 7. Consequently, current mmWave use cases are mostly limited to Line-of-Sight (LOS) communication. Advanced beam-steering algorithms for both transmitters and receivers are required to maintain reliability.

Another promising solution to mitigate channel degradation in mmWave communications is the use of Reconfigurable Intelligent Surfaces (RIS) [32], which was introduced in

5G-Advanced and is envisioned for 6G. RIS enables programmable surfaces that can dynamically steer the propagation of radio waves, thereby enhancing wireless communication performance. However, both advanced beam-steering and RIS technologies are still in the early stages of development and are not yet mature for large-scale commercial deployment. Further technology advancements and extensive real-world validation are needed to enable 5G mmWave to reliably support a wider range of industrial applications in various environments beyond LOS scenarios.

Unified Spectrum Regulation and Device Support

One major concern in the industrial wireless community is the lack of unified regulations on spectrum allocation across different countries, which not only places a burden on device manufacturers, but also limits the options available to 5G users when selecting products. This issue is even more pronounced in the mmWave band, as devices struggle to simultaneously support wide frequency ranges, due to hardware limitations and cost constraints.

7 Impact of Aggressors and Assessing Performance of Industrial Wireless Systems

As mentioned in Section 1, 5G is a promising candidate for integrating wireless technology into many industrial use cases. However, achieving high-reliability and low-latency is particularly challenging due to the stochastic nature of the wireless channel and the physical constraints posed by over-the-air transmissions—such as significant signal loss, degradation from multipath, and co-channel interference. This becomes even more pronounced for IWNs, described in [33, 34], which are deployed in harsh environments where industrial wireless channels are reflective and dynamic due to the presence of metallic surfaces and constantly moving personnel or objects, all of which can severely impact communications. IWNs could suffer from various aggressors, a term introduced by the IEEE P3388 working group [35] to collectively describe RFI sources, multipath effects, and other factors that degrade network performance. Ensuring consistent performance in the presence of aggressors is a major challenge for 5G in IWNs, especially for mission-critical and time-sensitive applications that require deterministic latency and high reliability.

Besides the impact from aggressors, the diversity and variability of IWN environments further increase the difficulty of 5G adoption. Channel conditions vary significantly across industrial sectors and use cases. Even within the same industrial sector, IWN performance can exhibit considerable discrepancies due to differences in the work zone geometry, wall material, object placement, and various RFI sources [36]. In many dynamic environments these influencing factors can evolve over time, further complicating the feasibility and evaluation of 5G deployment. Therefore, the degradations in performance caused by aggressors and the dynamic nature of IWNs emphasize the need for a standardized performance assessment and validation process to encourage the adoption of 5G.

In this section, we introduce the various types of aggressors and their potential impact on 5G performance, followed by a discussion of the key challenges faced in IWNs. Finally, we present an emerging IEEE standard for evaluating performance of IWNs and discuss how it can support and enhance 5G deployment in various industrial use cases.

7.1 Aggressors in Industrial Wireless Networks

Figure 5 shows the classification of industrial wireless aggressors, which was defined in IEEE 3388. Physical aggressors refer to factors that degrade wireless signal performance due to the physical environment, which include path loss, multipath effects, and blockages. Physical aggressors are more complex and dynamic in IWNs, therefore, the performance degradation and uncertainty level in the communication channel are higher compared to home/office environments.

Electromagnetic aggressors refer to any form of electromagnetic emissions within the frequency band of the IWN. These aggressors can be categorized into coexisting communications and non-communications-based interference. Coexisting communications aggressors arise from external wireless network activity that shares the same spectrum as the in-

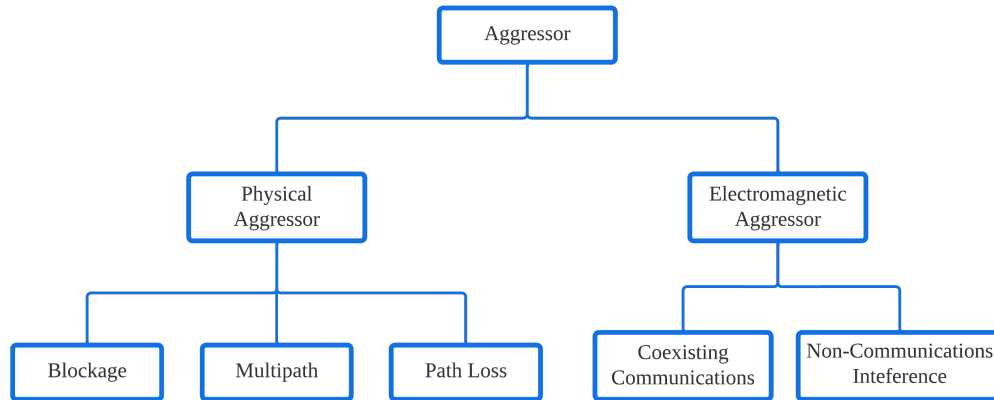


Figure 5: Classification of industrial wireless aggressors defined in IEEE 3388 [10].

tended network. Non-communications interference originates from sources that produce non-communications RF emissions. These RF emissions include industrial microwaves, welding equipment, RF jamming, and radar signals. Electromagnetic aggressors can cause collisions and detection errors in wireless transmissions, leading to increased packet loss and increased latency. Figure 6 presents examples of the impact of an electromagnetic aggressors on 5G performance. We obtained the results from experiments with our 5G testbed, and we compared the latency performance under varying power levels of interference from welding that was injected into the communication channel. We observed an increase in packet delay and jitter as the power of the welding EMI source increased.

Slot format	Welding Source Distance (m)	Latency Performance				
		Jitter (ms)	Avg (ms)	Min (ms)	Max (ms)	Stdev (ms)
1-1-3	no welding RFI	0.191	9.025	4.754	18.912	1.652
1-1-3	12	0.424	10.192	4.835	26.879	2.376
1-1-3	9	0.453	10.102	4.82	23.164	2.414
1-1-3	6	0.213	11.035	4.748	20.926	2.543
1-1-3	3	0.465	12.301	4.892	26.465	3.023
3-1-1	no welding RFI	0.355	8.516	4.951	23.128	1.59
3-1-1	12	0.35	9.751	4.7	26.442	2.356
3-1-1	9	0.159	9.997	4.791	25.468	2.411
3-1-1	6	0.558	10.137	4.77	59.238	2.497
3-1-1	3	0.181	11.332	4.768	40.677	2.658

Figure 6: Impacts to 5G latency performance from welding interference. The slot format illustrates the DL-SL-UL slot number configured for each transmission period. The latency performance is measured through iPerf with a 6 Mbps DL traffic.

7.2 Challenges of Validating Performance of Industrial Wireless Networks

When 5G or other wireless networks are deployed, the performance of a specific IWN is often evaluated under ideal conditions or simulated channel models, which hardly accurately captures the full impacts of aggressors. Below, we highlight some key challenges that we consider important for 5G adoption.

The Accuracy of Modeling and Simulation

The highly complex and dynamic nature of industrial wireless communications channels makes it challenging to accurately reproduce these conditions using conventional simulation or analytical modeling techniques. Modern ray tracing approaches lack the fidelity required to accurately simulate highly reflective environments. Advanced modeling methods with the help of onsite measurements are needed in order to improve the simulation results. Figure 7 shows the simulation results from [37], where industrial channel characteristics were incorporated into a simulation model using channel measurements from a factory environment. The figure illustrates the packet-error-rate (PER) against the signal-to-noise (SNR) ratio curves for different simulated channels, with the blue and red curves representing improved results from real LOS and NLOS channel measurements, while the other three curves correspond to results from simulation that used the TGN model proposed by the IEEE WLAN Working Group [38]. From Figure 7, one can observe a significant difference in performance of the real industrial channel compared to the existing simulated models. Signal degradation due to NLOS channels, the red trace, cannot be neglected even under conditions of high SNR, highlighting the need for more accurate performance assessment models for IWNs, to avoid overestimation.

Difficulties of Performance Evaluation Using Real Equipment

One primary cause that hinders the adoption of 5G is the uncertainty of system performance in actual industrial deployments. The actual performance may not align with vendor's marketing targets due to the differences between the actual deployment and vendor's test deployment. Therefore, end users need the ability to test and evaluate realistic system performance before deploying an IWN. This assessment helps optimize deployment strategies, understand network requirements and limitations, and fine-tune configurations.

While deploying a wireless network directly in its actual industrial environment can provide the most realistic conditions, it comes with significant constraints in terms of flexibility, controllability, and repeatability. Conducting on-site testing is often impractical due to the high costs and time requirements, and a single deployment cannot comprehensively test the system across various communication scenarios with different setups. The dynamic and unpredictable nature of industrial wireless channels makes it difficult to assess network performance under consistent and repeatable network conditions.

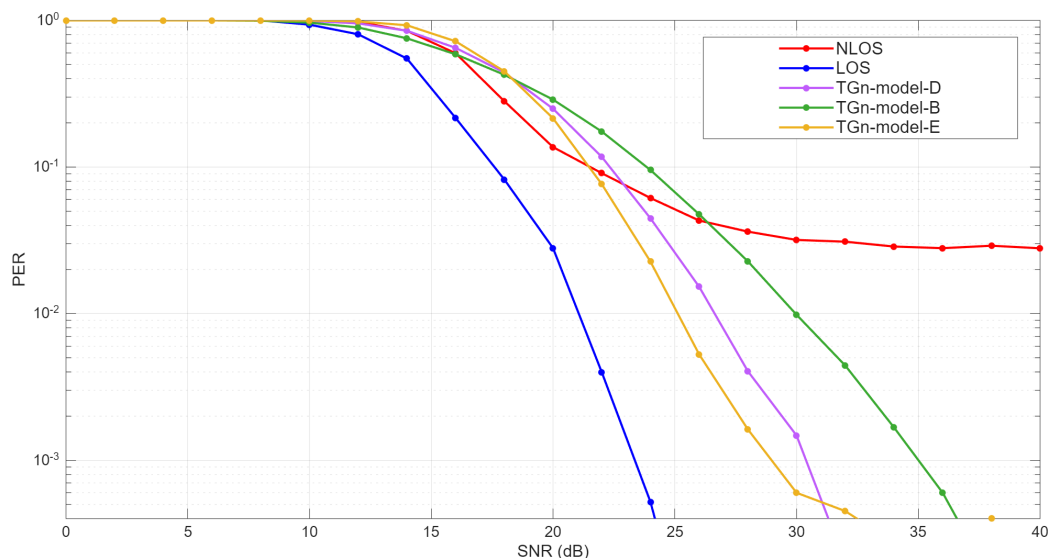


Figure 7: A comparison between the PER-SNR curves, from [37], which was generated using industrial LOS/NLOS channel data from an automotive plant (blue/red traces) and the existing TGN models from the IEEE WLAN WG [38].

Simulation studies could be a practical alternative; however, they also have limitations. The primary hurdle is achieving a useful level of fidelity that is indistinguishable from experiments that use real-world network equipment and traffic generated by industrial applications and devices. Therefore, we recommend that building 5G-integrated testbeds to emulate real-world deployments is useful for accurately assessing performance. In our previous work [19], we presented an industrial 5G testbed with a controllable RF channel as a balanced approach between real-world deployments and simulations. This approach enabled high-fidelity performance evaluation under realistic industrial RF conditions and traffic while maintaining flexibility in network configuration and setup. More work is needed to implement real-use cases and configuration optimization to improve network performance.

Advanced Methods for Reproducing Aggressors

Due to the unique characteristics of industrial wireless channels, reproducing channels that reflect realistic propagation environments becomes necessary during network testing and evaluation. Field measurement data taken from actual sites capture channel characteristics, supporting the channel reproduction process. Generally, the channel reproduction can be realized in several ways: simulated using simulation models, reproduced through channel emulators, or reproduced through anechoic and reverberation chambers. In order to accurately capture industrial channel characteristics, advanced techniques are used to complement conventional methods by introducing better data processing tools.

Machine learning techniques were proposed to implement high-accuracy channel mod-

els with clustering of channel features. For example, various clustering methods were introduced to capture the characteristics of channels from wireless measurements [39, 40]. Another work, which we are actively pursuing, is to utilize machine learning to automatically reproduce physical industrial wireless environments with a reverberation chamber.

Advanced methods for the reproduction of electromagnetic aggressors are also needed, as they are beneficial for studying the performance of the protected network under realistic interference conditions. These methods include simulation modeling, signal replication techniques, and the integration of replicated aggressors into system-level testing. For example, a playback approach for the RFI generated from Tungsten Inert Gas (TIG) welding was proposed in [41]. In [19], a 5G testbed was introduced to support measurement-based research of 5G networks to create controlled channels subject to wireless aggressors.

While existing studies on aggressors and channel reproduction have established an initial foundation for the enhancement of test methodologies, there are still opportunities in this area. These opportunities include the design of more effective machine learning models for channel reproduction, the creation of reference simulation models for various types of RFI aggressors, standardized reproduction procedures and test vectors for arbitrary interference sources, and the generalization of these processes for broader deployments and implementations.

Lack of Real-World Measurement Data

The lack of sufficient measurement data from real-world industrial environments presents another challenge to be solved. To enable more accurate experimental studies, field measurements are needed for both physical and electromagnetic aggressors across various industrial use cases. Capturing the wireless channel impulse response (CIR) or power delay profile (PDP) is essential for characterizing industrial channel behavior, which can then be leveraged for models in simulation, physical channel emulation, and feature extraction. Currently, more measurement data from actual deployment sites are needed.

In addition, measurements of various types of RFI aggressors are equally important. These measurements can support the modeling or reproduction of RFI, thereby improving the realism and reliability of industrial wireless network evaluations.

7.3 Standardized Performance Assessment for Industrial Wireless Systems

Wireless communications are inherently more challenging in industrial environments due to the presence of various aggressors. One of the biggest concerns for industry stakeholders is the inability to validate whether 5G or other wireless technologies can meet the QoS requirements of their specific use cases. Currently, IWN deployments lack a standardized testing and performance assessment framework. Therefore, standardized models are needed for various network degradation factors, test architectures, and industrial user requirements.

These needs have driven the development and work published by the IEEE P3388 working group [35] and the published IEEE 3388 standard [10]. The standard establishes models representing RF environments, test methodologies, and evaluation processes for industrial wireless networks. It outlines a framework for wireless device manufacturers, system integrators, and end users to replicate RF channels, assess devices, and measure network performance in controlled and repeatable ways. Figure 8 illustrates the recommended standard performance assessment process by the IEEE 3388 standard for the deployment of IWNs. The whole multi-step evaluation process includes guidance on assessment planning, testing and measuring, results analysis, and performance reporting, which supports the final decision making on the deployment of IWNs.

Another important target within the roadmap of IEEE P3388 working group is to develop profiles that follow the standardized framework. Profiles of industrial sectors and aggressor specifications are under development, helping system developers and integrators better understand the behavior of IWNs. Future scenario-specific profiles are projected to describe environmental setups, traffic QoS requirements, and potential aggressors. Meanwhile, classification, realistic modeling, and signal reproduction methods for non-communications electromagnetic aggressors are to be proposed. These profiles are applicable not only to industrial channel reproduction in testing, but also to the refinement of existing network simulation frameworks.

The development of the IEEE 3388 standard may be beneficial in supporting the adoption of 5G in industrial wireless networks. The standard helps system integrators validate whether 5G is a suitable candidate for their use case scenarios. Through the evaluation process, QoS can be verified under the impact of realistic aggressors. Further network configuration and enhancement may also be optimized based on the results.

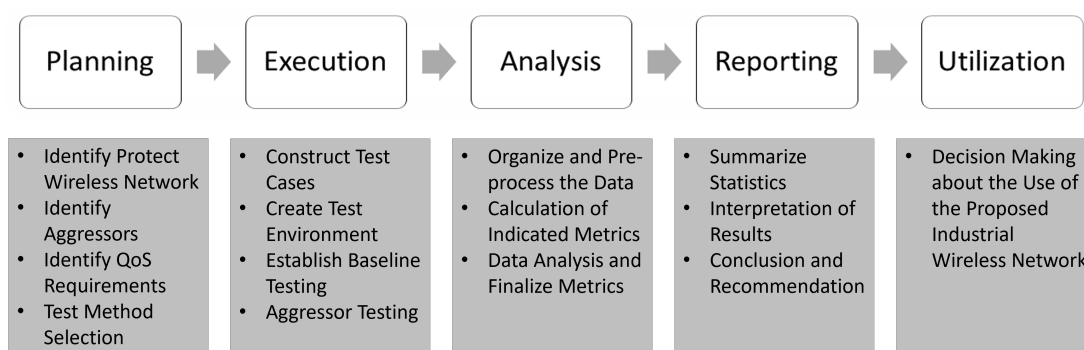


Figure 8: Performance assessment process with corresponding procedures and actions in different stages for deploying an industrial wireless network recommended by IEEE 3388 standard.

8 Network Instrumentation and Channel State Information Exposure

Building an instrumented network system is essential for assessing performance and properly dimensioning the network. This need has expanded with the development of the 5G RAN Intelligent Controller (RIC) and the emergence of digital twins, where real-time (or near real-time) network status monitoring is vital. In the previous section, we focused on measurement and evaluation methods related to aggressor impacts and end-to-end performance assessment. This section highlights the challenges of internal monitoring capabilities of 5G networks, particularly in the software-based RAN.

Enhancing RAN instrumentation offers several benefits. It enables internal system evaluation and optimization, including delay measurements between various protocol stack layers. Such insights help to identify bottlenecks and estimate per-hop latency, which can be further utilized for network dimensioning and optimization. Intelligent RAN control, anomaly detection, and energy savings are all important aspects for network instrumentation.

Currently, measurement tool support is limited for software-based 5G RANs, and there are several challenges to overcome. The most significant challenges are related to the limited platform capabilities. As mentioned in Section 4, the network performance of a software-based 5G system is highly dependent on hardware capabilities. Running additional instrumentation would further increase the computational burden on 5G devices. The extra monitoring or data logging inevitably degrades system performance when hardware processing power and write speeds are limited. As a result, internal instrumentation is currently used primarily for non-real-time applications or debugging.

Another major challenge is capturing channel state information (CSI) and exposing it to the upper layers. As diverse use cases continue to grow, different types of metrics are required. However, extracting user-defined wireless CSI remains difficult. Monitored data are often limited to what the system inherently provides rather than what users need. CSI is not only useful as input for scheduling and the RIC but can also be leveraged for application-level control and optimization. An emerging field for industrial wireless applications is wireless co-design. To accommodate the losses and delays in wireless, control systems may be co-designed to accommodate the wireless medium, such that the reliability of the use case is preserved. A representative example is smoothing robotic movement and control when faced with bursty delays or packet errors. This process is triggered when the signal quality metric falls below a certain criteria. To broaden the usage of co-design for 5G, the industrial community needs access to more useful CSI metrics.

More advanced instrumentation tools should be developed. Currently, few open source tools exist and each of them has their own limitations. T-tracer [27] is a comprehensive logging tool designed for the OAI RAN, but this tool could significantly degrade the RAN performance due to processing overhead. LatSeq [26] provides latency measurements with low impact on system performance, yet it requires post-analysis and lacks of the ability to expose data in real time. Extended Berkeley Packet Filter (eBPF)-based tools, which have

been adopted in a recently developed AI-RAN platform, can instrument the system without affecting the RAN performance [42]. The AI-RAN platform addresses the challenges mentioned here and provides solutions with low performance impact; there are still limitations in latency for real-time data exposure. More work is required to achieve real-time data exposure with a low impact to RAN performance.

9 Conclusion

In this report, we discuss the results from our interviews with the industrial wireless community on the challenges with 5G that prevent widespread adoption. We identify the key challenges in using software-based private 5G networks for industrial applications. We explore the difficulties in maintaining QoS requirements for time-critical industrial applications. We highlight the importance of mmWave support and the associated challenges. The unique characteristics of industrial wireless environments are also discussed, emphasizing the need for standardized testing and measurement methods, which underscores the significance of the emerging IEEE 3388 standard. We address the need to internally instrument, expose useful network metrics, and examine the gaps in tool support.

In summary, while software-based private 5G networks have a great potential for industrial deployment, several technological gaps remain. From the perspective of the industrial wireless community, the development of 5G and beyond must align with market expectations. Simplified and easy-to-manage systems are essential, and standard implementations should be guided by the practical needs of real-world use cases. Moreover, verifying the QoS of applications within actual industrial environments is critical to accelerate 5G adoption. Many solutions are still insufficient to support time-sensitive applications that require deterministic behavior. Greater efforts are needed in optimizing systems, developing communication techniques that are resilient to environmental aggressors, and rigorous performance testing with validation.

Through this report, we highlight existing gaps and challenges and offer insights and directions for future advancements in 5G and beyond. Ultimately, our goal is to support the use of software-based 5G networks as a viable solution for mission-critical and time-sensitive industrial applications, facilitating broader adoption.

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