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Review

Industry 4.0 and Beyond: The Role of 5G, WiFi 7, and Time-Sensitive Networking (TSN) in Enabling Smart Manufacturing

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Abstract: This paper explores the role that 5G, WiFi 7, and Time-Sensitive Networking (TSN) play in driving smart manufacturing as a fundamental part of the Industry 4.0 vision. It provides an in-depth analysis of each technology's application in industrial communications, with a focus on TSN and its key elements that enable reliable and secure communication in industrial networks. In addition, this paper includes a comparative study of these technologies, analyzing them based on several industrial use cases, supported secondary applications, industry adoption, and current market trends. This paper concludes by highlighting the challenges and future directions for adopting these technologies in industrial networks and emphasizes their importance in realizing the Industry 4.0 vision within the context of smart manufacturing.

Keywords: Industry 4.0/5.0; cyber-physical manufacturing systems; Industrial IoT; millimeter-wave; smart manufacturing; 5G/6G; TSN; WiFi 7/8; IEEE 802.11be

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1. Introduction

Smart manufacturing (also known as the smart factory concept) is a revolutionary concept that aims to transform the manufacturing sector through the utilization of modern technologies [1]. The objective of smart manufacturing is to create a more productive, flexible, and eco-friendly manufacturing system that can adapt to changing market needs and, consequently, boost the overall performance of manufacturing processes. The successful implementation of smart manufacturing relies heavily on the effective use of the Industrial IoT (IIoT) and industrial communications [2–4]. The IIoT enables seamless connectivity between machines, systems, sensors, and human operators, facilitating real-time data exchange, which is crucial for optimizing production processes, ensuring quality control, and supporting predictive maintenance. This interconnected environment allows for more efficient decision making and enhances the flexibility and responsiveness of manufacturing systems to meet evolving demands. This combination of physical and digital systems is a central part of the fourth industrial revolution (also known as Industry 4.0) [5,6], which is transforming conventional industrial automation and control systems into sophisticated cyber-physical manufacturing systems. A reference architecture called the Reference Architecture Model for Industrie 4.0 (RAMI 4.0), developed by the German Industrie 4.0 Platform in 2015, enables the implementation of Industry 4.0 [7]. Beyond Industry 4.0, we expect to see an environment where autonomous machines and humans collaborate to achieve common goals. This further evolution is often referred to as Industry 5.0, although the concept is still emerging in the academic literature. Unlike Industry 4.0, which focuses on automation and the IIoT, Industry 5.0 emphasizes the integration of human creativity and intelligence alongside advanced technologies to create more sustainable, resilient, and human-centric manufacturing systems [8–12]. According to the European Commission, Industry 5.0 is centered on sustainability, focusing on human well-being and environmental considerations while still leveraging technological advancements [13]. This vision aims to balance the power of technology with a human touch, fostering collaboration between humans and machines to enhance both productivity and social responsibility. Technologies such as augmented and extended reality (A/XR), autonomic systems, and 6G networks [14] are anticipated to play a key role in realizing this vision by enabling more autonomous, self-adjusting manufacturing systems that can anticipate and respond to fluctuating market needs. However, as Industry 5.0 evolves, it is important to account for both technological and human factors, ensuring that advancements serve not only economic growth but also social and environmental sustainability [15,16]. The industrial evolution in the context of smart manufacturing is summarized and illustrated in Figure 1.

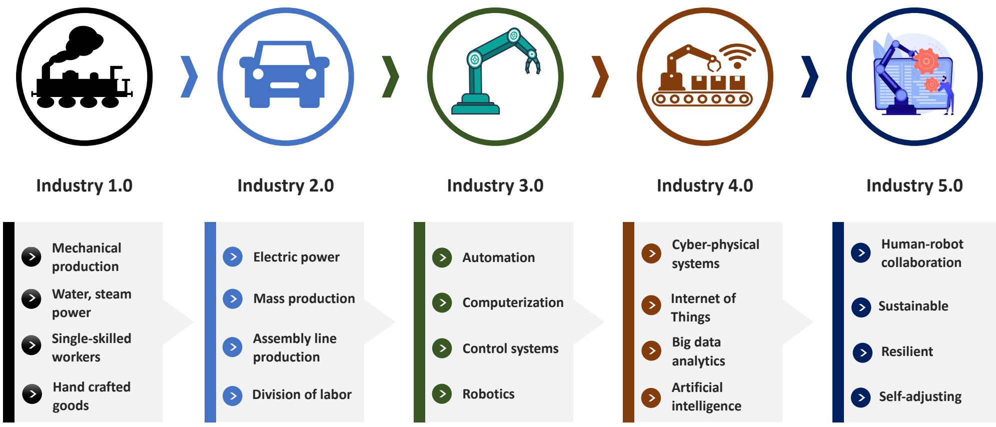

Figure 1. Industrial evolution in the context of smart manufacturing.

Recent developments in communication technologies such as 5G, WiFi 7, and time-sensitive networking (TSN) are expected to be key enablers of smart manufacturing in the Industry 4.0 and beyond era. These technologies have the potential to completely change the way industrial devices communicate with the digital world, allowing a vast number of industrial machines to be connected to the Internet and interact with an array of IT applications used to manage industrial organizations, thus enabling the development of faster, more efficient, and more responsive manufacturing systems.

The introduction of 5G networks has opened up new possibilities for wireless communication, especially in the field of smart manufacturing. Fifth-generation networks specify an advanced cellular infrastructure that offers significant improvements in terms of speed, capacity, and low latency compared to previous generations, supporting not only traditional mobile broadband services but also a wide range of machine-to-machine communication services [17]. The high-speed and low-latency capabilities of 5G, combined with features such as the New Radio interface, network slicing, and software-defined networking (SDN), are expected to provide the foundation for a highly connected and efficient industrial ecosystem. Advanced error correction codes, mmWave, massive MIMO, and improved signal processing in 5G further enhance reliability and performance, making it possible to connect a large number of devices and sensors in real time. These capabilities make 5G an ideal solution for smart manufacturing and Industry 4.0, allowing for the seamless exchange of data between machinery, systems, and devices.

WiFi 7, the latest development in wireless local area network technology, boasts an array of technical features, such as the use of higher-order modulation (4096 QAM), multi-link operation, wider bandwidth, multi-AP operation, and WiFi sensing, providing the enhanced connectivity and increased efficiency needed in Industry 4.0 and beyond [18]. The high modulation order enables fast data transmission, while multi-link operation allows a device to connect to the network using multiple links, thereby enhancing reliability, performance, and capacity. The extended bandwidth of WiFi 7 allows more data to be sent, thus reducing latency and enhancing effectiveness. Multi-AP operation, by operating numerous access points as one entity, ensures uninterrupted coverage even in large facilities, while WiFi sensing offers integrated location-based services and enhanced asset tracking.

Time-sensitive networking, a set of standards under development by the IEEE 802.1 working group, facilitates the development of smart manufacturing. This technology includes some unique features, such as time synchronization, bounded end-to-end latency, dependability, and resource/network management, which guarantee real-time communication and control between devices [19]. Fine-grained time synchronization across all devices on the network allows these devices to collaborate, while bounded end-to-end latency guarantees an expected response time. Additionally, TSN's high reliability ensures that communication and control systems remain in working order even when network failures occur. Furthermore, resource and network management offer an effective distribution of network resources, giving priority to critical data transmission. Wireless TSN takes these advantages to a higher level, enabling real-time communication and control for mobile devices and machines, particularly in places where wired solutions are not practical.

The objective of this paper is to examine the role of 5G, WiFi 7, and TSN in driving smart manufacturing in the Industry 4.0 and beyond era. We provide a comprehensive overview of the key enabling features of these technologies and their applicability in the context of future smart manufacturing. This paper also compares these technologies, evaluates their impact on smart manufacturing use cases, and discusses the trade-offs and potential synergies between them. To stimulate future research, we discuss a number of challenges and promising future research directions associated with the evolving smart manufacturing landscape.

The rest of this paper is structured as follows. In Section 2, we provide an overview of the key technologies in 5G private networks specifically designed for industrial communications. Section 3 discusses the key features of WiFi 7 and its relevance in industrial settings. Section 4 covers the characteristics of TSN and provides details about TSN over wireless networks such as WiFi and 5G. A comparative analysis of these communication technologies is presented in Section 5. In Section 6 we highlight the challenges and future directions of industrial communication technologies. Finally, we conclude this paper in Section 7.

2. Industrial Communications with 5G

With the evolution from 4G to 5G, more varied usage scenarios and applications for cellular networks are supported beyond voice, messaging, and mobile broadband. Fifth-generation networks support four service categories: enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications, massive machine-type communications, and fixed wireless access, which the International Telecommunication Union's Radio Communication Sector (ITU-R) has identified for the 5G era [17]. By integrating 5G networks into their information and communication systems, enterprises can enhance the performance of their systems and operations by taking advantage of the enhanced capabilities of 5G networks. Some of these capabilities are as follows:

- **Flexible numerology** for radio resource allocation [20,21]: 3GPP outlines two main frequency ranges for 5G NR use, called frequency range 1 (FR1) and frequency range 2 (FR2). FR1 is also known as the sub-6 GHz band, while FR2 is referred to as the millimeter-wave (mmWave) band. The maximum channel bandwidth and the space between OFDM subcarriers can vary depending on the specific frequency range being used. The concept of flexible numerology allows for variations in both the value of subcarrier spacing and the duration of OFDM symbols, impacting the available data rate and transmission latency.

These subcarrier spacings are obtained by scaling up the LTE-based subcarrier spacing $\delta f = 15$ kHz by 2^{μ}, leading to a range from 15 kHz up to 240 kHz, with a proportional change in cyclic prefix duration. This allows tailoring radio access parameters to suit the unique demands of industrial applications, like achieving low latency for real-time control or high throughput for data-intensive tasks. Furthermore, the adaptability of numerology allows for different applications with varying requirements to operate together within the same frequency band, resulting in optimal spectrum usage [22]. This can lead to enhanced efficiency and productivity in manufacturing processes, as well as improved automation and quality control beyond what other wireless technologies can offer.

- **mmWave** communication [21,23,24]: The allocated mmWave radio spectrum provides much more bandwidth than is available in the sub-6 GHz band, allowing for the accommodation of a wide range of novel applications for Industry 4.0 and beyond. Example applications include advanced smart industrial functions like vision-guided robots, ultra-high-definition video and imaging for remote visual monitoring and inspection, smart safety instrumented systems, intelligent logistics, and high-precision image-guided automated assembly, among others. The availability of ultra-reliable and low-latency communications (URLLC) in factory automation scenarios enables smart machines and robots to work alongside humans or cooperate toward a common goal, which is a key aspect of the future Industry 5.0 vision. Furthermore, utilizing mmWaves enables not only thorough communication but also sensing, which can support seamless and adaptive behavior in equipment and machines, allowing them to detect nearby individuals or objects and react appropriately by adjusting their movements or slowing their operating rate.
- **Beamforming** [25–27]: Antenna beamforming employs an array of multiple antenna elements to generate a directed beam. This has the significant advantage of reducing interference in sub-6 GHz bands, resulting in higher throughput due to directional transmission. At mmWave frequencies, beamforming is essential for reliable communication, as it enhances channel gain. Beamforming, for example, facilitates concurrent communication among collaborative robots in a smart industrial environment.
- **Massive MIMO** [28–33]: Massive MIMO utilizes a large number of antennas to exploit spatial degrees of freedom, enabling it to support communication with multiple devices simultaneously without requiring additional time or frequency resources [34]. As industrial environments tend to contain metallic surfaces from equipment, many such environments are challenging for wireless communication. Massive MIMO's channel-hardening effect improves its immunity to fast fading and allows for more deterministic communications, which is important for many industrial applications with strict quality-of-service requirements.
- **Network Slicing** [35]: Next-generation factories will need to handle diverse traffic flows that may have conflicting needs for performance, reliability, and security. A single large system cannot meet the demands of these new industrial situations. Slicing permits the delivery of a variety of specific services with potentially incompatible requirements on a single physical 5G substrate [36].
- **The 5G LAN-Type Service** [37]: Most current automation systems in industry are based on a range of proprietary wired local area network (LAN) technologies. These systems allow devices to communicate directly with each other across the LAN, discover their services, and utilize multi-cast communication and other LAN features. This contrasts with 5G communication modes, which are more peer-to-peer oriented and rely on switching and routing in the 5G core network. The 5G LAN-type service [38] is designed to replicate LAN features and simplify communication between 5G-based devices, particularly in industrial automation environments [39].

The manufacturing industry is rapidly adopting 5G wireless communication technology to automate industrial processes. The 5G network must be integrated with the industrial facilities and equipment when it is deployed in an industrial manufacturing facility. Typically, a dedicated, private 5G network tailored to the requirements and services of the plant is needed. It can be difficult to achieve good radio reception in a manufacturing setting. Particularly in large factories, the location of the machinery and assembly lines makes it difficult to communicate using line of sight. Additionally, factory floors are often environments with significant radio signal scattering due to the presence of tools and machines that affect shadowing and radio signal interaction in diverse ways. During production, both humans and robots move around carrying out their duties, creating a highly dynamic environment. Therefore, careful radio planning is required prior to installing a 5G system in a factory. Depending on the industry's unique requirements, a private 5G network is typically chosen to meet the demands for high-performance, dependable, and secure networks for mission-critical applications. A public 5G network would be a preferable choice if the enterprise merely needed a general-purpose network for basic communication applications.

The integration of 5G wireless communication technology is anticipated to yield better outcomes in other vertical marketplaces such as healthcare, agriculture, supply chain logistics, and energy management. A key requirement for 5G industrial applications is access to the appropriate radio spectrum, with the 3.5 GHz range being the most commonly used globally harmonized band. The wider selection of spectrum options available in 5G, particularly in licensed frequency bands, can meet a broader range of requirements and lower the cost of network equipment and devices. In modern manufacturing, where large amounts of data are generated, the integration of various communication technologies is essential, with 5G technology providing not only high data rates and ultra-low latency to enable fast transmission and analysis of data, but the standard also specifies interfaces in the core network to integrate other wireless technologies such as WiFi and LoRa. An overview of the manufacturing use cases enabled by 5G is provided in Table 1.

Table 1. Manufacturing use cases enabled by 5G [40–42].

Use Case	Reliability	Device Costs	Device Density	Low Latency	Band-Width	Flexibility	Ubiquity	Location-Awareness
Advanced predictive Maintenance	✓	✓	✓					
Precision Monitoring & Control			✓	✓				
Augmented Reality & Remote expert				✓	✓			
Remote Robot Control				✓				
Manufacturing-as-a Service		✓				✓	✓	
Automated Guided Vehicle	✓			✓				✓
Drone Inspections	✓			✓				✓

3. WiFi 7 for Industrial Communications

IEEE 802.11be, also referred to as WiFi 7, is the latest wireless local area network (WLAN) technology that supports the connectivity requirements of smart manufacturing in the Industry 4.0 and beyond era. The technology offers several key features that make it a suitable choice for industrial environments, where real-time communication, security, and high-speed data transfer are critical. Some of the key technological features of WiFi 7 [43], along with their applicability in smart manufacturing, are as follows:

- **High Modulation Order:** WiFi 7 utilizes Orthogonal Frequency-Division Multiplexing (OFDM) with a modulation order of up to 4096-QAM [44], allowing it to transmit at very high data rates within a given bandwidth, such as for vision-based applications. In the context of smart manufacturing, the significance of high data rates extends beyond the transmission of large volumes of data, as it also enables the ultra-low-latency transmission of small data packets within short timeframes, which is desirable in many industrial applications. Industrial processes that benefit from high data rate services include machine-to-machine communication, real-time monitoring, and production optimization, where the ability to swiftly transmit data is critical. It is worth noting that a signal-to-noise ratio (SNR) of approximately 40 dB is required at the receiver end to accurately decode a 4096-QAM signal, a threshold that may not always be attainable in many environments [43]. However, antenna beamforming can help alleviate this problem by increasing the channel gain.

- **Multi-Link Operation:** WiFi 7 has an additional characteristic called multi-link operation, which allows the access point and end devices to function concurrently over 2.4 GHz, 5 GHz, and 6 GHz frequency bands, thereby providing multiple channels for data transmission [45,46]. This feature aims to enhance network performance by increasing peak throughput, minimizing latency and jitter, and augmenting network reliability. It ensures that even if one connection fails, essential data will still be delivered, making WiFi 7 networks more dependable [47]. Additionally, link aggregation can be performed to significantly increase network throughput. In the industrial domain, these features are especially useful for processes such as machine-to-machine communication and real-time inventory control, where a dependable network is essential for proper and effective performance.
- **Wider Bandwidth:** A distinguishing characteristic of WiFi 7 is its expanded bandwidth. After the initial adoption of 802.11ax, the WiFi industry is increasingly utilizing the 6 GHz band to swiftly enhance the peak throughput of WiFi, which will have a significant impact on industrial use cases. Consequently, discussions have arisen about the most optimal methods for utilizing the available unlicensed spectrum, ranging up to 1.2 GHz between 5.925 and 7.125 GHz, which more than doubles the bandwidth compared to the 5 GHz band alone [18]. By providing a wider bandwidth, WiFi 7 has the potential to support a large number of industrial devices. Moreover, operating in a less congested frequency spectrum also reduces interference, which can be a challenge in industrial settings where many systems and devices operate in close proximity.
- **Multi-AP Operation:** WiFi 7's multi-AP operation allows multiple access points to work together as a single, continuous network. This feature can facilitate seamless handovers between WiFi networks, simplify overall network configuration (e.g., selecting operating channels), and enhance the capacity of the WiFi network [48]. By synchronizing multiple access points, coverage can be extended across the entire factory floor, guaranteeing that all machines and mobile devices maintain a reliable and strong connection. Furthermore, cooperation among neighboring APs through the exchange of crucial scheduling information and channel state information (CSI) is a potential strategy to enhance the utilization of scarce radio resources [43], particularly in an industrial environment with a high density of sensors and actuators, where co-channel interference can reach intolerable levels.
- **WiFi Sensing:** Wireless radio sensing is a cutting-edge feature of WiFi that allows WiFi networks to sense and detect the presence of people, objects, and other devices, even when they are not actively transmitting data. In smart manufacturing, WiFi sensing has a range of important applications, including enabling location-based services, asset tracking, and improved safety and security. Location-based services allow for real-time tracking of machines, devices, and personnel across the factory floor. Asset tracking is another significant application of WiFi sensing, ensuring that costly machinery and equipment are not misplaced or stolen. By detecting the presence of these assets, manufacturers can monitor their usage, maintenance schedules, and movements, ensuring they are always in good working condition and ready for use. Furthermore, WiFi sensing can be key to improving the safety and security of the smart factory [49]. By detecting people and machines, WiFi sensing helps ensure a safe and secure work environment for all personnel by preventing accidents. For instance,

WiFi sensing can alert workers to dangers in areas where machinery may pose a risk, allowing them to take appropriate measures.

The features of WiFi 7 and its usage in smart manufacturing are summarized in Figure 2. These features enable advanced smart manufacturing applications, including collaborative robots, augmented reality, and predictive maintenance. However, WiFi 7 is not without its limitations. Due to its higher modulation and higher carrier frequency, the range of WiFi 7 signals is likely to be reduced compared to previous generations operating at lower frequencies. This could be an issue in certain industrial environments where devices, machines, and systems are spread out over a large area. In addition, since the standard has not yet been ratified, it is unclear when WiFi 7 access points and client devices will be commercially available.

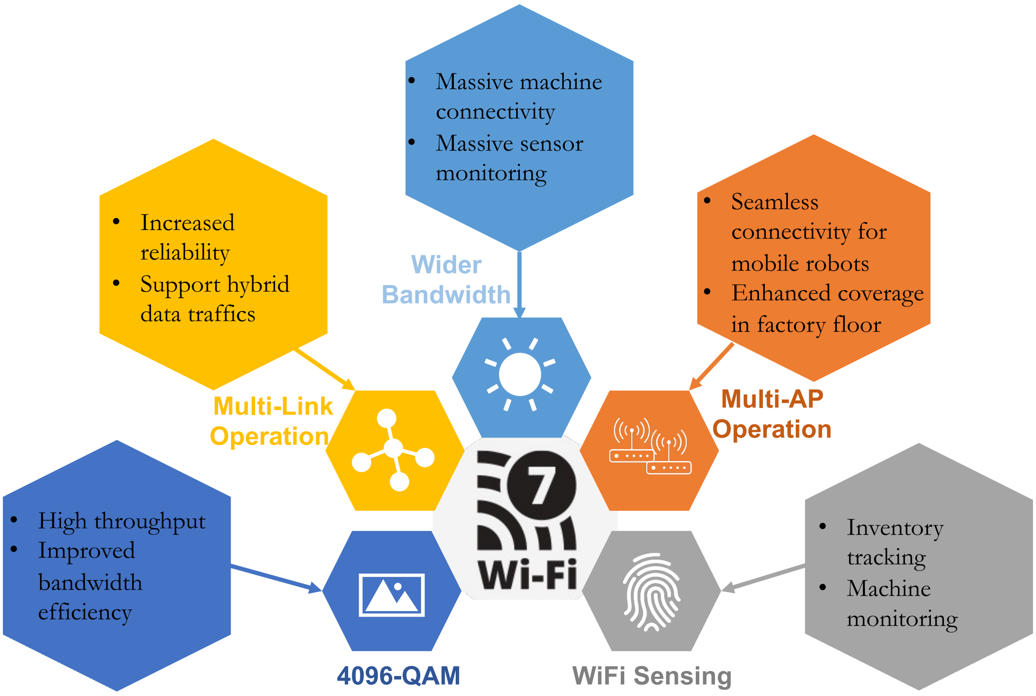

Figure 2. Key features of WiFi 7 and their applications in smart manufacturing.

4. TSN for Industrial Communications

Real-time communication technologies that can provide guaranteed delivery of critical messages in a timely manner are of utmost importance in many manufacturing industries. Today, there exists a wide variety of wired and wireless communication technologies. Industrial use cases that demand ultra-high reliability and low latency, such as control systems in automation applications, robotic motion control, and safety-critical systems, rely on several dedicated open (e.g., PROFINET) and proprietary Ethernet protocols (e.g., EtherCAT, Ethernet/IP) [19]. These protocols, collectively known as Real-Time Ethernet, are built upon Ethernet's legacy features, which were mainly designed to handle best-effort traffic. OPC-UA (Open-Platform Communications—Unified Architecture) is another crucial communication standard. It is a platform-independent, service-oriented machine-to-machine communication interface and is considered the de facto communication standard for Industry 4.0 [50]. Recently, there has been an emerging trend in integrating OPC-UA with time-sensitive networking (TSN) to deliver real-time, deterministic data exchange and ensure interoperability [51–53]. TSN is a set of standards introduced to provide communication networks with real-time capabilities, such as zero/extreme low packet loss and bounded end-to-end latency. In this section, we aim to provide a brief overview of the key elements of TSN that support the vision of smart manufacturing.

TSN aims to achieve deterministic real-time communication through time-triggered message delivery in the network, where all the network elements are globally time-synchronized. TSN accommodates traffic flows that demand ultra-high reliability (zero loss), low jitter, and low latency on a bridged network, along with best-effort traffic. This is achieved by combining various mechanisms, such as traffic shaping, defining various traffic queues, and implementing appropriate scheduling schemes, as well as reliability measures such as redundant/parallel message transmissions. Figure 3 outlines the main features/mechanisms associated with TSN, along with the respective standards. They can be broadly categorized into four pillars: (1) time synchronization, (2) bounded latency, (3) ultra-high reliability, and (4) network/resource management [54,55].

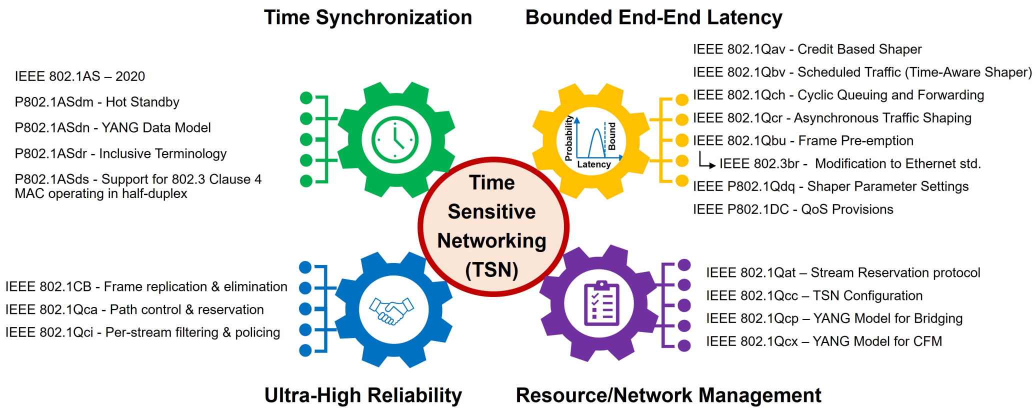

Figure 3. TSN: Features, key mechanisms, and associated standards [56].

Time Synchronization: To enable strictly bounded end-to-end latency and several other features, TSN requires precise time synchronization to sub-microsecond levels of accuracy among all network elements such as switches, bridges, and end devices (manufacturing robots, PLCs, etc.). TSN (wired) achieves this through the Precision Time Protocol (PTP—version 2) (IEEE 1588), using Ethernet frames in a distributed fashion to synchronize the timing of all network elements to that of a master device (known as the grandmaster). The TSN time synchronization standard, IEEE 802.1AS (a subset of IEEE 1588), defines a generalized PTP (gPTP) profile to extend the time synchronization approaches beyond wired networks to wireless TSN. The currently active standard IEEE802.1AS-2020 [57] covers the protocols and procedures involved in selecting the timing source (best master) in the network, the transport mechanisms for synchronized time, and indications of the occurrence and magnitude of impairments (e.g., phase and frequency discontinuities). The time synchronization mechanism is based on a master–slave approach, where all devices in the network are synchronized to the grandmaster (the device with the most accurate time source in the network) through periodic exchange of sync and follow-up messages over a spanning tree. IEEE 802.1AS is an evolving standard, and details of active amendments (P802.1ASdm, P802.1ASdn, P802.1ASdr, P802.1ASds) can be found in [57].

Bounded End-to-End Latency: In an industrial network, TSN adopts several mechanisms to provide the required end-to-end latency for different traffic classes, including time-critical messages. Special packet-handling approaches, such as traffic scheduling and traffic shaping techniques, are introduced to guarantee bounded latencies. In the early days, the development of TSN standards considered Ethernet as the physical layer, and IEEE 802.1Q is a standard that supports VLANs on an Ethernet network. According to this standard, the IEEE 802.1Q tag ("Priority Code Point" field—3 bit) defines eight types of traffic classes, each having its own separate queue per Ethernet port. Various mechanisms (defined by IEEE 802.1Qav, IEEE 802.1Qbv, IEEE 802.1Qbu, IEEE 802.1Qch, and IEEE 802.1Qcr) [55] can be used to achieve different QoS levels across the eight queues in multi-hop switched networks. IEEE 802.1Qbv (Time-Aware Shaper) manages time-critical traffic flows based on a time-triggered scheduling approach. Each queue has a transmission gate that is opened/closed in a cyclic fashion for a particular time duration based on a gate control list (GCL). IEEE 802.1Qav (Credit-Based Shaper) defines the operation of traffic flows with relaxed latency bounds. A "credit"-based transmission strategy is adopted to allocate bandwidth (logically) to all traffic classes and thus prevent the starvation of lower-priority traffic [58,59]. IEEE 802.1Qbu (Frame Preemption) specifies the suspension/holding of an ongoing low-priority best-effort traffic (preemptable) transmission by a high-priority traffic flow (express traffic) to meet latency bounds. The associated IEEE 802.3br amendment defines two MAC interfaces: express and preemptable. Only a frame mapped to an express interface can preempt the frame mapped to a preemptable interface. IEEE 802.1Qch (Cyclic Queuing and Forwarding) specifies assigning message frames to egress queues according to their arrival time. IEEE 802.1Qcr (Asynchronous Traffic Shaper) also shapes the incoming traffic with the help of a "credit" counter and schedules prioritized over non-prioritized traffic, per hop, without the need for synchronization among various network elements. The IEEE P802.1Qdq amendment describes the recommended shaper parameter settings for bursty traffic needing bounded latency, and IEEE P802.1DC specifies the QoS features for a networked system rather than a bridge.

Reliability: This is another critical requirement for industrial networks in the smart manufacturing domain. Most communication technologies handle reliability through re-transmission mechanisms, which is not an option for time-critical traffic flows. IEEE 802.1CB (Frame Replication and Elimination) ensures reliability in TSN networks through redundant frame transmissions across disjoint paths. IEEE 802.1Qca (Path Control and Reservation) handles the creation of multiple paths in the network by extending the application of Intermediate System to Intermediate System (IS-IS). It also specifies explicit path control, data flow redundancy, and distribution of control parameters for scheduling and time synchronization. IEEE 802.1Qci (Per-Stream Filtering and Policing) specifies the procedures for filtering frames of a particular data stream (using rule matching to filter StreamIDs). It also addresses policing aspects to ensure that the systems/devices conform to the agreed configurations (e.g., allocated bandwidth) to guarantee QoS to different data streams.

Resource/Network Management: Proper configuration/management of various network elements (e.g., bridges, switches, end devices) and resources, such as bandwidth, communication paths, and schedules, are crucial to achieving TSN's low latency and highly reliable communication capabilities. IEEE 802.1Qat (Stream Reservation Protocol) deals with reserving resources and schedules between the source and the destination to achieve the desired end-to-end QoS. IEEE 802.1Qcc specifies three TSN network configuration models: fully centralized, hybrid, and fully distributed [60]. Several data flows (streams) between end devices (acting as talker/listener) co-exist in a TSN. The User/Network Interface (UNI) deals with the exchange of configuration information, such as join/leave requests, resource configuration/releases for a particular stream, or status responses, between end users and the network. In a fully centralized model, end devices send their requirements to an entity called the Centralized User Configuration (CUC), which passes these details to the Centralized Network Configuration (CNC) device. Accordingly, the CNC manages all the streams and schedules in the network. In a hybrid model, the user's requirements are passed directly to the network, and the CNC does the configuration without the existence of the CUC in the network. In a fully distributed model, neither the CNC nor CUC exists. The configuration data exchanges between bridges use YANG models (a data modeling language), as specified in IEEE 802.1Qcp. IEEE802.1Qcx specifies the YANG models associated with fault management in the connectivity. Currently, both of these are part of the active IEEE 802.1Q-2022 standard [61].

4.1. TSN over Wireless

Although time-sensitive networking is, in principle, independent of the MAC layer, all the TSN mechanisms detailed above were specified over the last few years assuming Ethernet as the MAC layer. Extending these mechanisms to the wireless domain is essential for smart manufacturing applications, and ongoing work aims to adapt TSN mechanisms to operate over a wireless medium. Emerging wireless technologies such as 5G and WiFi 7 are expected to revolutionize the industrial sector by untethering several industrial applications, making it more flexible, mobile, and reconfigurable at lower costs (installation and maintenance) [62]. Many of these applications demand deterministic latency and ultra-reliability, and hence TSN needs to be extended into the wireless domain since these applications/use cases will be implemented over a hybrid network (containing both wired and wireless devices), if not being completely wireless.

The wireless nature of the communication medium introduces several challenges, including dynamic link quality, packet error rates (especially in harsh industrial environments), shared medium access, interference due to other wireless transmissions, unlicensed spectrum, and the mobility of end devices. In this section, we discuss how well TSN capabilities can be extended/integrated with 5G and WiFi 7, along with the ongoing efforts to meet the demands of the smart manufacturing industry using a hybrid wired-wireless TSN network.

4.1.1. TSN over WiFi

WiFi is currently the most widely used wireless technology in the industrial domain, and the latest WiFi generations, IEEE 802.11ax/IEEE 802.11be, have several features that enable the integration of TSN mechanisms. Precise time synchronization among all the network elements is crucial in TSN. Time synchronization in 802.11 is achieved through the Fine Timing Measurement (FTM) protocol, an improvised version of the Timing Measurement (TM) protocol. In FTM, a station computes and adjusts its synchronization error and frequency drift with respect to its AP via repeated exchange of time-stamped FTM frames and their acknowledgments (ACKs). Previous research shows that hardware-based timestamping can achieve precise time synchronization (10–40 ns) compared to software-based time synchronization techniques (1 µs) [58]. According to IEC/IEEE 60802 (the TSN profile for industrial automation), the maximum tolerable synchronization error is 0.1–1 µs for factory automation networks (from the grandmaster). HW-based timestamping approaches using System-On-Chip solutions (e.g., FPGAs) are currently favored, as SW timestamping on current COTS wireless cards/modems cannot achieve the required time synchronization accuracy [63]. IEEE 802.1AS-2020 specifies the use of FTM for TSN integration over 802.11. It is essential to note that FTM message exchanges should not affect TSN traffic flows or vice versa. In a hybrid TSN network, wireless TSN can be at the edge of the network (acting as the last mile) or act as a bridge between two wired TSN networks. Hence, it is essential to ensure smooth integration/translation of time synchronization across wired and wireless domains.

Traffic classification, shaping, and scheduling mechanisms are vital in extending TSN capabilities to the wireless domain. Industrial WiFi networks must manage hard real-time, soft real-time, and best-effort traffic through proper traffic classification methods. IEEE 802.11 (2016) [64] supports traffic classification using VLAN tags, employing traffic specification (TSPEC) and traffic classification elements (TCLAS), using the "traffic ID (TID)" field present in the IEEE 802.11 header. This is in accordance with the TSN traffic classifications specified in the IEEE 802.1Q standard and helps ensure seamless integration between wired and wireless networks.

To support real-time traffic, efficient medium access control (MAC) is critical in 802.11, rather than relying on the default contention-based MAC approaches. Several enhancements in IEEE 802.11ax and IEEE 802.11be support time-critical traffic flows. The "Trigger Frame" (TF)-based medium access scheme seems promising compared to other MAC mechanisms such as EDCA, HCCA, TWT, etc. [58]. In addition, OFDMA and MU-MIMO capabilities help reduce contention and achieve low latency by enabling simultaneous transmissions to/from multiple users. Thus, the access point can deterministically schedule communications with the 802.11 devices in the network. As discussed earlier, a time-aware schedule (IEEE 802.1Qbv) defines the coordinated opening/closing of gates to prevent best-effort traffic from interfering with time-sensitive frames. Time-aware traffic scheduling (IEEE 802.1Qbv) can be achieved by reserving resources on top of efficient 802.11 MAC operation (e.g., TF-based access, EDCA). The multi-link operation capability in WiFi 7 (discussed in Section 3) can help end devices establish multiple links (thus, multiple channel access opportunities) with the access point (AP). The newer 6 GHz band will likely be preferred for time-critical traffic flows, while the congested 2.4/5 GHz band can handle other traffic. Using the Stream Classification Service, an AP can allocate resources to the stations with time-critical flows within the BSS, thus mapping TSN traffic scheduling requirements (from 802.1Qbv) onto 802.11be MAC. IEEE 802.11be also introduces "restricted target wake time (rTWT)" service periods (SPs) scheduled by APs in a BSS for handling time-sensitive traffic, and each station is expected to stop its transmission before the rTWT SP. Multi-AP coordinated operation is another critical feature in 802.11be for efficiently allocating channel resources in overlapping BSSs to handle time-sensitive traffic.

Ultra-high reliability is another major challenge for wireless TSN networks due to the wireless nature of the medium. Reliability is mainly handled using redundancy mechanisms at the intra-frame and inter-frame levels. In 802.11ax, the most reliable modulation and coding scheme (MCS) is MCS = 0 with BPSK (redundancy of 1/2). Another scheme introduced in 802.11ax for better reliability is dual-carrier modulation, where redundant data transmission occurs over different subcarriers. Inter-frame redundancy is achieved using ACK-based retransmissions or by sending extra copies of the same frame through different paths/resources without waiting for an ACK. Multi-link operation in WiFi 7 can enhance reliability through redundant transmissions over multiple links to a single AP or several APs. The multi-AP coordination feature helps make use of redundant links across non-collocated APs.

4.1.2. TSN over 5G

Private 5G networks and their capabilities, as discussed in Section 2, are emerging wireless solutions for the smart manufacturing domain. Combining TSN capabilities with 5G helps address the URLLC requirements of Industry 4.0. The architecture (e.g., considering a fully centralized TSN configuration model) and functionalities required for 5G–TSN integration are discussed in 3GPP Release 16. The 5G system mainly consists of two components: a radio access network (comprised of UEs and gNBs) and a 5G core (5GC) network. The core network comprises different network functions associated with the user plane and control plane elements. The 5G system (5GS) is modeled as one or more logical/virtual TSN bridge(s) within the TSN network for 5G–TSN integration in 3GPP Release 16, as shown in Figure 4. This logical 5GS TSN bridge has TSN translator functionality to establish connectivity with the other elements in the network, both at the device side (DS-TT: Device-Side TSN Translator) and at the network side (NW-TT: Network-Side TSN Translator). The DS-TT acts as an Ethernet port at the UE-side user plane, whereas the NW-TT user plane, integrated with the 5GC user plane function (UPF), acts as an Ethernet port for the 5GS toward the external data network. The NW-TT control plane is implemented as an application function (AF) and manages the interface toward the CNC. The AF passes the TSN configuration/management-related information provided by the CNC to the 5GC (control plane).

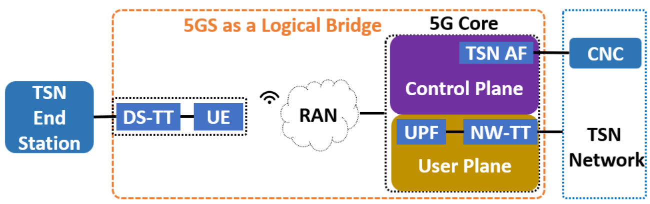

Figure 4. Integration of 5G system into TSN as a logical bridge.

Support for TSN time synchronization in 5G is defined by IEEE 802.1AS. The 5GS itself is a time-aware system with an internal synchronization mechanism that keeps all elements, such as gNB, NW-TT, DS-TT, etc., synchronized to the 5G internal clock. TSN synchronization represents another concurrent synchronization process in 5G–TSN integration. In this process, the TSN GM is outside the 5GS, and when a gPTP message (involved with the TSN synchronization discussed earlier) enters the 5GS through the NW-TT entity, the ingress timestamp (in terms of 5GS time) is added and then forwarded to the UE through the UPF. When this gPTP message reaches the DS-TT, the residence time in the 5GS is calculated with the help of an egress timestamp, included in the gPTP message, and sent to the external TSN elements. The 3GPP Release 17 discusses uplink TSN synchronization and UE–UE synchronization, where the TSN GM can be from the UE side. In this case, the DS-TT acts as the ingress port and the NW-TT as the egress port for the TSN gPTP messages.

The 5GS features several mechanisms for enhanced reliability when integrated with TSN. These mechanisms include multi-antenna transmissions, the use of multiple carriers, and packet duplication over different radio links in the 5G network. Redundancy in PDU sessions, UEs, and RAN dual connectivity, with increased radio resource usage, ensures reliability within the 5GS virtual bridge, an element of the TSN network. In addition to user plane redundancy, the 5G core network supports redundancy by enabling control plane network functions that can be deployed in multiple locations (e.g., edge, data centers).

Flexible numerology and configuration of OFDM signals are vital for enabling low latency in 5G networks. Shorter subframe slots and mini-slots are key enablers of low latency in 5G–TSN systems. The 5G new radio also supports the preemption concept, allowing URLLC transmissions to preempt non-URLLC data transmissions. Network slicing techniques and the 5G LAN-type service can be employed to handle time-critical TSN flows.

5. A Comparative Analysis

In Sections 2–4, we discussed the major features of 5G, WiFi, and TSN networks (both wired and wireless) that can enable smart manufacturing applications. In this section, we aim to provide a detailed comparative analysis of these technologies mainly from four perspectives: industrial use cases, supported secondary applications, industry adoption, and current market trends, as summarized in Figure 5.

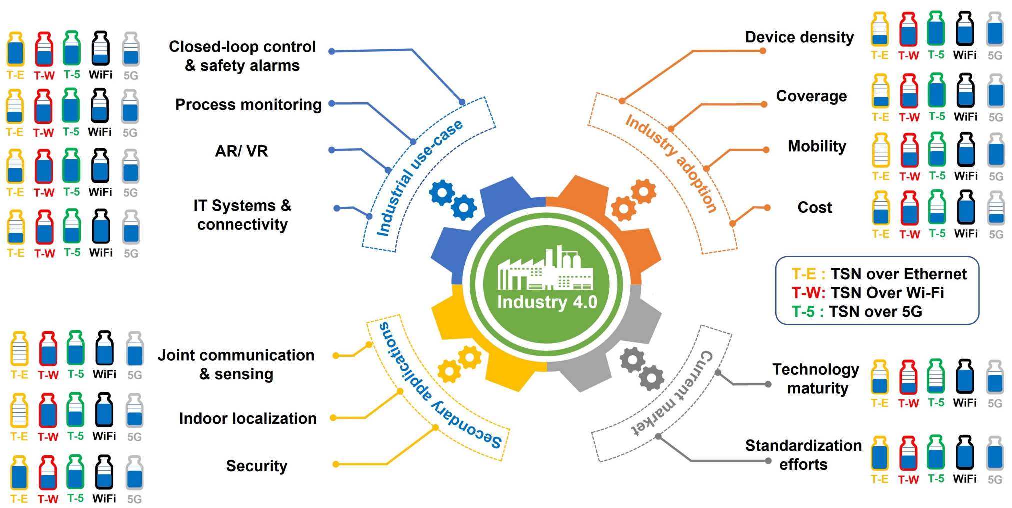

Figure 5. Comparison of communication technologies for Industry 4.0 and beyond.

For the first dimension, we look at the industrial use-case perspective. There are a wide variety of use-case classifications in the literature [40,65], and here we capture a consolidated, broader application-oriented classification of them. Closed-loop control and safety-critical alarms/systems are the hard real-time applications in smart manufacturing that demand ultra-reliability and very low latency, and TSN over Ethernet (T-E) is the best solution. However, scenarios that need flexibility demand wireless communication options, and we know that the wireless medium always adds reliability/latency challenges. Among all the available wireless technologies, we believe TSN over 5G (T-5) has the advantage of combining the features of TSN over a dedicated spectrum, and hence it is better suited to handle such applications. WiFi is the least preferred choice due to the unlicensed spectrum implementation and associated interference and wireless channel contention issues. Process monitoring use cases involve monitoring various parameters through different sensors. Such applications are relatively lenient in latency and reliability compared to closed-loop control applications, and the data-rate requirements generally tend to be small. However, wider coverage is essential, as many processes in the process industry cover large industrial spaces, and wireless technologies would be a better choice than T-E as they eliminate wiring requirements. In these use cases, 5G provides a better range than WiFi, and TSN integration provides additional reliability. Thus, T-5 is better suited for process monitoring use cases than T-W and 5G, whereas WiFi seems the least preferred wireless technology for process monitoring. MR/VR/AR are emerging technologies widely used in smart manufacturing to represent a digital 3D virtual factory for various applications, including training. These applications generally demand a very high data rate and flexibility to move around (hence, T-E is the least preferred). Both 5G and WiFi can provide higher data rates, and TSN integration offers additional capabilities for better reliability.

The second dimension focuses on the secondary services these technologies can provide in addition to their primary role of providing communication infrastructure for manufacturing applications. Both 5G and WiFi (and their TSN-integrated versions) can offer sensing capabilities along with wireless communication. Indoor localization is another capability provided by both 5G and WiFi (and their TSN-integrated versions). Localization using WiFi is relatively established in comparison with 5G-based localization. These features are not feasible over wired TSN. Security is another major factor that needs to be considered in connection with communication technologies. Wireless technologies are more prone to security threats compared to wired infrastructure. Between 5G and WiFi, the unlicensed spectrum makes WiFi more exposed.

The third dimension involves the various factors smart manufacturing industries consider while adopting these technologies onto their production floors, in addition to the technical capabilities/offerings. Compared to WiFi, 5G offers broader indoor coverage (including its TSN integrations), and TSN over Ethernet requires physical cabling to provision the T-E devices/switches. These aspects also influence device density. T-E requires an individual cable for each client. Although WiFi supports a possible bandwidth of 320 MHz, a factory floor will have multiple APs with overlapping coverage areas. If an AP is operating with 320 MHz bandwidth, the entire available spectrum is consumed, and the nearby APs will use the same channels, resulting in interference. Hence, it is not practical for each AP to make use of this wider channel. The 5G mmWave band supports multiple carriers of 100 MHz, and carrier aggregation helps obtain wider bandwidth, enabling dense device deployment. The smart factory floor consists of several mobile devices, such as autonomous intelligent vehicles (AIVs), drones, etc. Another factor is how well these technologies support mobility. Although WiFi and 5G enable mobility, 5G provides smoother and more reliable handovers. TSN integration creates challenges if devices are highly mobile, as the network configuration maintained by the CNC would need to be updated very often. Cost is another vital factor behind the industry's adoption. WiFi is a more cost-effective solution than private 5G networks and their TSN-integrated versions.

The fourth dimension we consider is the latest trends in the market. Most enterprises adopt a technology once it is relatively mature and stable. WiFi is the most used wireless technology in smart manufacturing today, whereas private 5G networks are slowly gaining adoption. Several industries are currently carrying out private 5G proof-of-concept evaluations. The current lack of availability of native private 5G devices is a concern, even though a few Release 15/16 products are available on the market. Similar scenarios exist when it comes to TSN. Several products support TSN over Ethernet; however, TSN integration over wireless (5G and WiFi) is in the early stages and is also dependent on the standardization process. While the standards for T-E, WiFi, and 5G are established, and newer releases are forthcoming, the standardization process for TSN integration into WiFi and 5G is in the early stages.

6. Challenges and Future Directions

6.1. Dynamic Network Management

Dynamic network management plays a pivotal role in enhancing communication performance across factory floors to handle the dynamic and often unpredictable changes in the environment caused by metallic surfaces and the movements of various objects, including robots, automated guided vehicles, and other metallic objects, as well as the dense deployment of wireless devices. Dynamic network management is critical in facilitating the optimal allocation of network resources, ensuring quality of service (QoS), and adapting to changing network conditions to enable efficient and reliable industrial operations [66].

The evolution of 5G technology is expected to focus on further enhancing network slicing capabilities to cater to the diverse requirements of Industrial IoT use cases. This involves tailoring network slices to specific application needs, such as ultra-low latency, ultra-high dependability, and the ability to handle massive connections [67]. Additionally, the integration of edge computing capabilities into 5G networks and the 5G LAN-type service offer the potential for low-latency processing and an improved user experience. In this context, dynamic network management and fast packet switching play a critical role in efficiently allocating resources between the central cloud and edge nodes, thereby supporting latency-sensitive applications [68].

As WiFi 7 is anticipated to introduce improved multi-user MIMO methods, enabling multiple devices to transmit data simultaneously, dynamic network management becomes essential for optimizing scheduling and resource allocation for numerous users. This optimization process takes into account channel conditions, traffic patterns, and user priorities. To maximize spectrum utilization and alleviate congestion, existing spectrum access strategies, such as dynamic spectrum sharing or cognitive radio, may be adopted in WiFi 7, and new techniques need to be discovered. In this scenario, dynamic network management will facilitate the dynamic selection of the most suitable spectrum bands and their allocation to different WiFi services. Furthermore, future WiFi networks are expected to incorporate enhanced QoS methods to support a wide array of applications with varying requirements. Enhanced dynamic network management will be required to provide differentiated QoS based on application types, latency sensitivity, bandwidth demands, and traffic prioritization. The discovery of such adaptive approaches to network management will ensure the efficient utilization of resources and the seamless delivery of services tailored to the specific needs of different applications [66].

6.2. Deployment Issues

The deployment of private 5G networks in manufacturing environments requires careful investigation, as traditional 5G deployment approaches may not suit the unique communication requirements of factory floors or processing plants. Hence, revisiting and rethinking base station placement policies is essential to tailor private 5G networks for diverse use cases in smart manufacturing. On the other hand, upgrading to a new WiFi standard may necessitate the replacement or upgrading of old devices to support the new standard. Maintaining backward compatibility with older WiFi protocols can also be difficult. As the number of WiFi devices grows, the available unlicensed spectrum may become congested, resulting in performance loss. Effective spectrum management and coexistence strategies will be critical for WiFi 7 implementation [69]. Interference from other devices or neighboring networks operating on the same or surrounding channels might degrade WiFi signals. For optimal implementation, proper channel allocation and interference mitigation strategies will be required [70]. All of this requires novel research in deployment approaches for nontraditional wireless environments and applications.

TSN necessitates careful network device configuration and management to achieve accurate time synchronization and prioritization of time-sensitive traffic. This can be difficult, particularly with large-scale installations. TSN is based on standardized protocols and network device settings. During deployment, ensuring interoperability across different vendors' equipment, resource allocation, and scheduling approaches can be difficult. TSN accommodates many forms of traffic on the same network infrastructure, including time-sensitive and standard Ethernet traffic. It can be difficult to achieve efficient network convergence while adhering to rigorous time requirements during deployment. Integrating TSN into existing networks and legacy systems might be difficult since it may necessitate equipment modifications or replacements to support TSN's time-sensitive features. Research to discover novel methods for TSN network configuration and deployment is required.

6.3. TSN-Grade Wireless Performance

To achieve TSN-grade performance over wireless communication channels, one must overcome several difficulties due to the special properties of wireless media and communication protocols. Due to interference and the stochastic nature of the channel, wireless systems typically have a much higher packet error rate (PER) than cable- or optical fiber-based communication systems. TSN features like bandwidth scheduling and reservation are very good at delivering low latency/jitter over Ethernet. These capabilities must take into account wireless link characteristics, such as achievable data rates and PER, which tend to change over time due to variations in the radio environment and interference. The 3GPP Rel-15-defined ultra-reliable and low-latency communications (URLLC) mode is a key 5G capability that enables TSN-grade performance. The URLLC mode, as explained in [71], offers low latency with high dependability for short packets in conjunction with the flexible 5G frame structure concept. Additionally, it includes established QoS improvements for multiple concurrently active configurable grants and semi-persistent scheduling. Also, the extension of 802.1 TSN protocols over 802.11 is, by default, in line with the overall TSN reference architecture because 802.11 is one of the 802 LAN transport alternatives. However, in order for extensions of the 802.1 TSN protocols to function effectively, they must support the 802.11 MAC/PHY.

Existing TSN services (such as scheduling implemented in network administration and configuration) and wireless networks (such as 802.11 and 5G) will require the definition of new abstractions and interfaces. To ensure predictable and dependable time-aware delivery of scheduled traffic across wired and wireless domains enabled by various wireless technologies, clear inputs, outputs, tasks, and responsibilities are required. The adoption and expansion of TSN networks over wireless networks will be facilitated by a standard interface to interact with wireless domains that abstracts the underlying wireless connectivity technology. This work might be conducted in cooperation between the Avnu Alliance and IEEE 802.1 standards groups and could potentially include the definition of new wireless-specific parameters (for example, as an extension to the current 802.1Qbv YANG model). This work could also influence wireless standard organizations, such as IEEE 802.11 and 3GPP.

6.4. Implementation Challenges

New standards, such as 5G and WiFi 7, introduce new technologies. Theoretically, several new features are available with these new standards. But from a practical point of view, significant efforts have to be made to implement them. Careful testing and fine-tuning of these new technologies, especially in the factory floor environment, will be required. In the case of a factory floor environment, the implementation of new features can be particularly challenging. This is because factory floors are often complex and dynamic environments, and new features can have a significant impact on the way that work is performed. As a result, it is important to carefully plan and test any new features before they are implemented in a factory floor environment. Also, purchasing and implementing new equipment, software, etc., requires extra study and testing. There is always a risk that new features will not work as expected or could introduce new problems or security vulnerabilities.

6.5. AI in Industrial Wireless Communications

We can design and implement practical communication technologies for various wireless channels in actual application environments when we have channel models that accurately depict the physical effects of these channels on transmitted radio signals. Traditional channel modeling techniques, such as stored channel impulse responses, deterministic channel models, and stochastic channel models, require an in-depth understanding of the subject matter and technical proficiency in radio signal propagation modeling through electromagnetic fields. They are extremely complex, involve several parameters, are unsuitable for predicting the statistical characteristics of wireless channels, and are not transferable to other communication settings. To avoid these difficulties and complexities, machine learning and artificial intelligence approaches can help. For example, a generative adversarial network (GAN) framework was proposed in [72] to address the autonomous wireless channel modeling issue without requiring extensive theoretical investigation or data processing. Another example is the interplay between RIS and AI in wireless communications, which was explored in [73].

Modern manufacturing industries have progressed from electronic automation systems to industrial digital machine communication. In order to gather and analyze data for guiding dynamic, intelligent systems in manufacturing, these systems need a high-speed connection. When 5G communications are combined with AI and big data, it becomes possible to analyze industrial data more quickly and make precise decisions based on the data. Smart factories provide better-connected machine ecosystems by using big data from interconnected devices powered by AI and 5G connectivity [74].

7. Conclusions

In this paper, we have presented a comprehensive analysis of 5G, WiFi 7, and TSN in smart manufacturing applications for the Industry 4.0 and beyond era. This paper highlights the potential benefits and challenges of adopting these technologies in industrial networks, emphasizing the need for further research and development to address issues of reliability, compatibility, and standardization. The comparative study of these technologies provides valuable insights into their industrial use cases, secondary applications, adoption trends, and market opportunities. The findings demonstrate that these technologies have significant potential to drive smart manufacturing toward the Industry 4.0 vision and beyond. While each technology has advantages and disadvantages with regard to particular industrial applications, further efforts should be made to realize this potential. It is hoped that this paper will serve as a useful resource for researchers, engineers, and industrial practitioners interested in smart manufacturing and the role of emerging technologies in driving this transformation.

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